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# Computational Physics for Space Flight Applications

Presented by:  
Robert A. Reed

NASA/GSFC Code 561  
Greenbelt MD, 20771  
robert.reed@nasa.gov

Supported in Part by:

- NASA Electronics Parts and Packaging (NEPP) Program
- Defense Threat Reduction Agency (DTRA)
- NASA Space Environment and Effects (SEE) Program
- NASA's James Webb Space Telescope (JWST)

# Outline

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- Introduction to space radiation effects in microelectronics
- Using applied physics to help NASA meet mission objectives
- Example of applied computational physics
  - James Webb Space Telescope
  - Single Event Effects in emerging microelectronic technologies
- Future directions in applied computation physics



# Space Radiation Environment

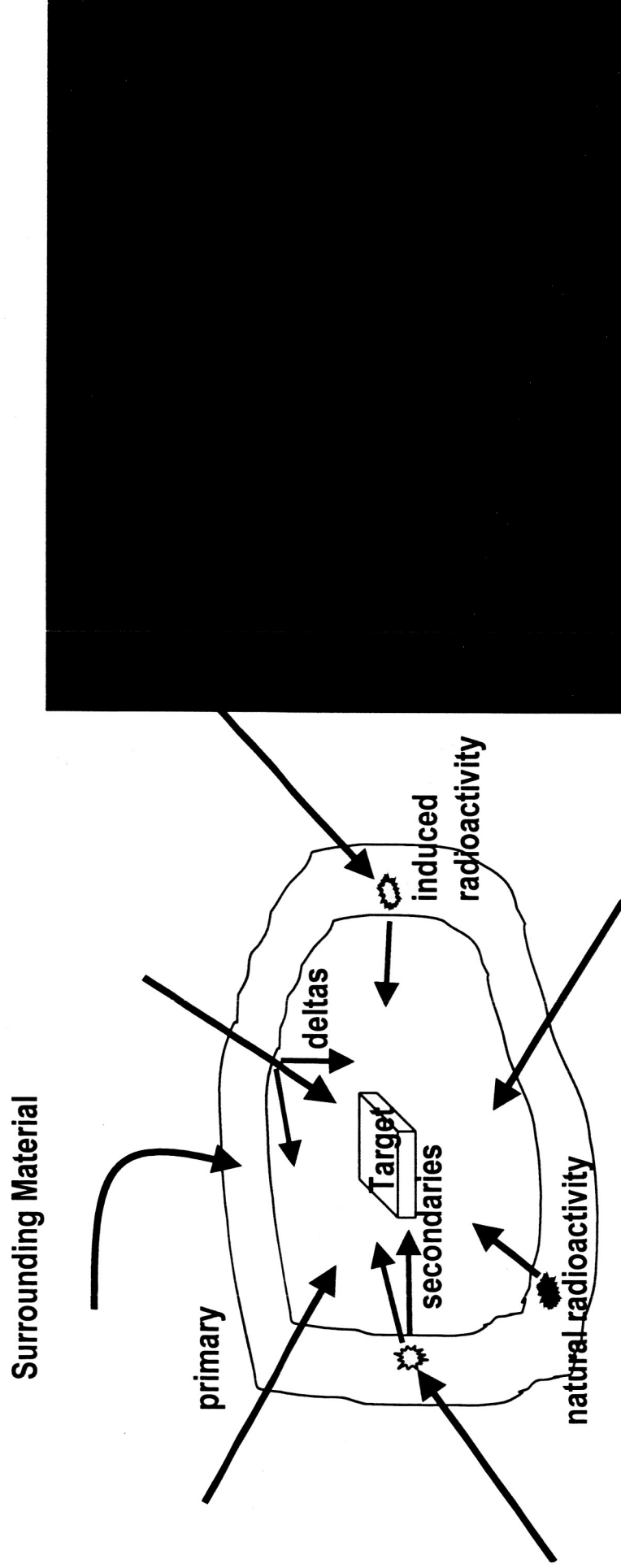
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Three portions of the natural space environment contribute to the space environment effects hazard

- Solar particles
  - Protons and heavier ions
- Galactic Cosmic Rays (GCR)
  - For earth-orbiting craft, the earth's magnetic field provide some protection for GCR
- Trapped particles (in the belts)
- Hazard observed is a function of orbit and timeframe
- Environment is dynamic, models are static

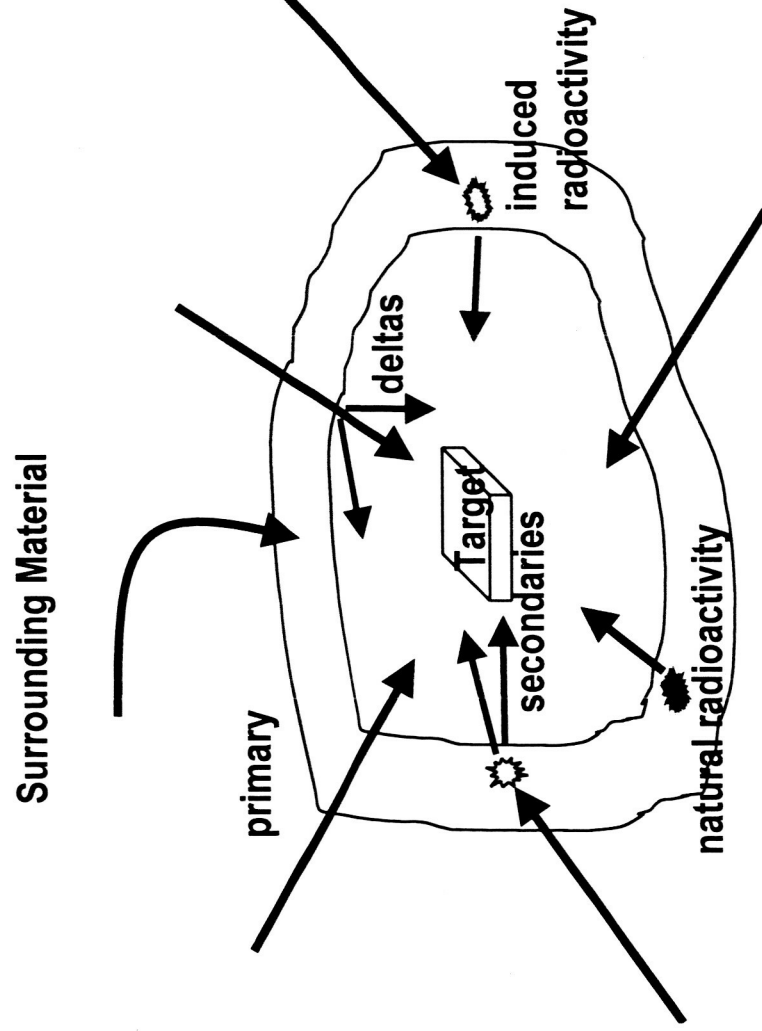


# Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets



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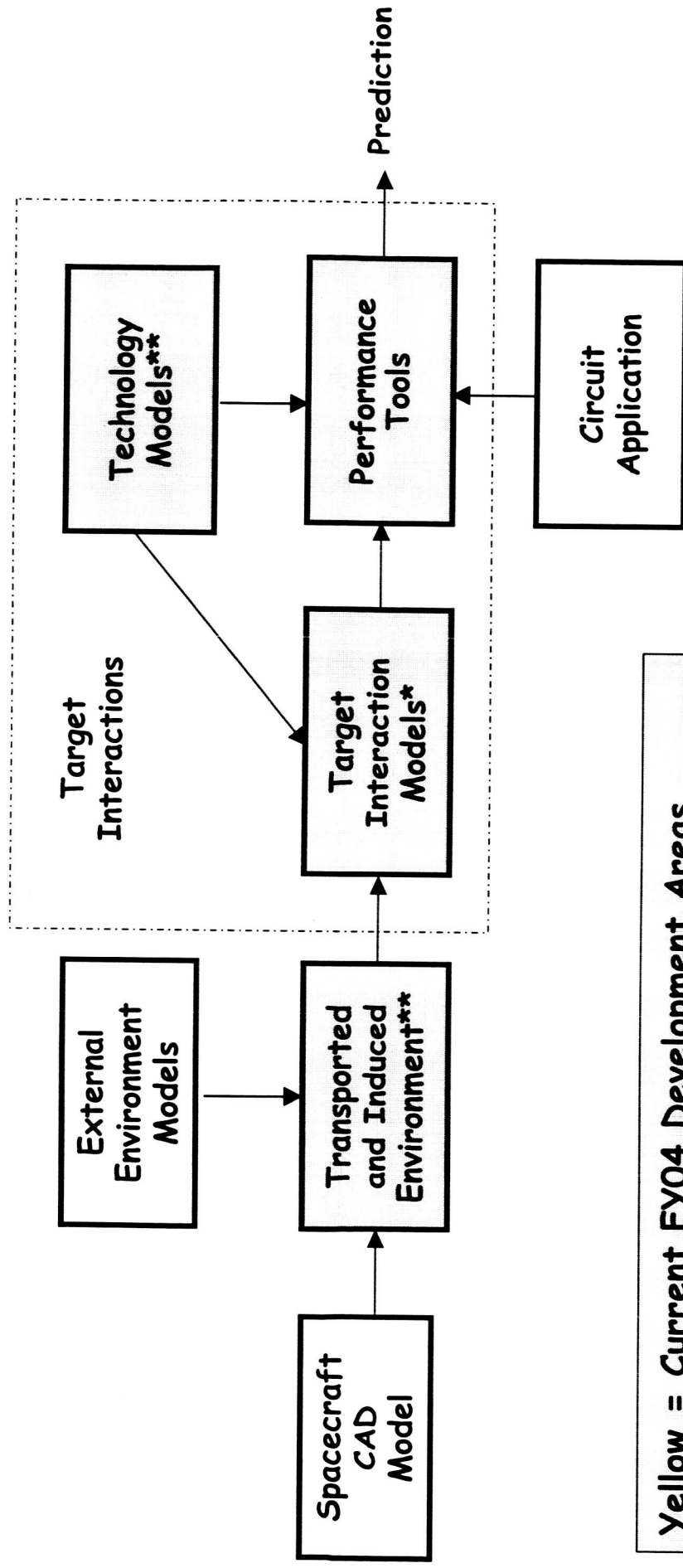


# Monte Carlo Based Computation Physics Tools Currently Used at NASA/GSFC

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- GEANT4
  - A multi-national team of physicists and engineers are developing Geant4 for the express purpose to Monte Carlo simulation of the passage of particles through matter.
  - Its application areas include high-energy physics and nuclear experiments, medical, accelerator and space physics studies.
- EMPC Inc.'s (a private company) NOVICE code suite
  - Developed to be a user-friendly, engineering tool for use, in part, by the space radiation effects community.
  - Its developer is highly regarded as an expert in radiation transport by the space radiation effects community.
- The Los Alamos National Laboratory's Monte Carlo N-Particle extended (MCNPX)
  - A general-purpose computer code that can be used for particle transport through materials.
  - Its application areas are similar to Geant4.
- NASA's Radiation Effects Array Charge Transport (REACT)
  - Simulation of charge transport through a semiconductor
  - Quasi-device physics (QDeP) code
- Clemson University Proton Interaction in Devices (CUPID)
  - Simulation of proton spallation reactions in Silicon
  - Tracks energy deposited in a right Rectangular Parallelepiped (RPP) volume

# Space Computational Radiation Interaction Performance Tools (SCRIPT)



Yellow = Current FY04 Development Areas

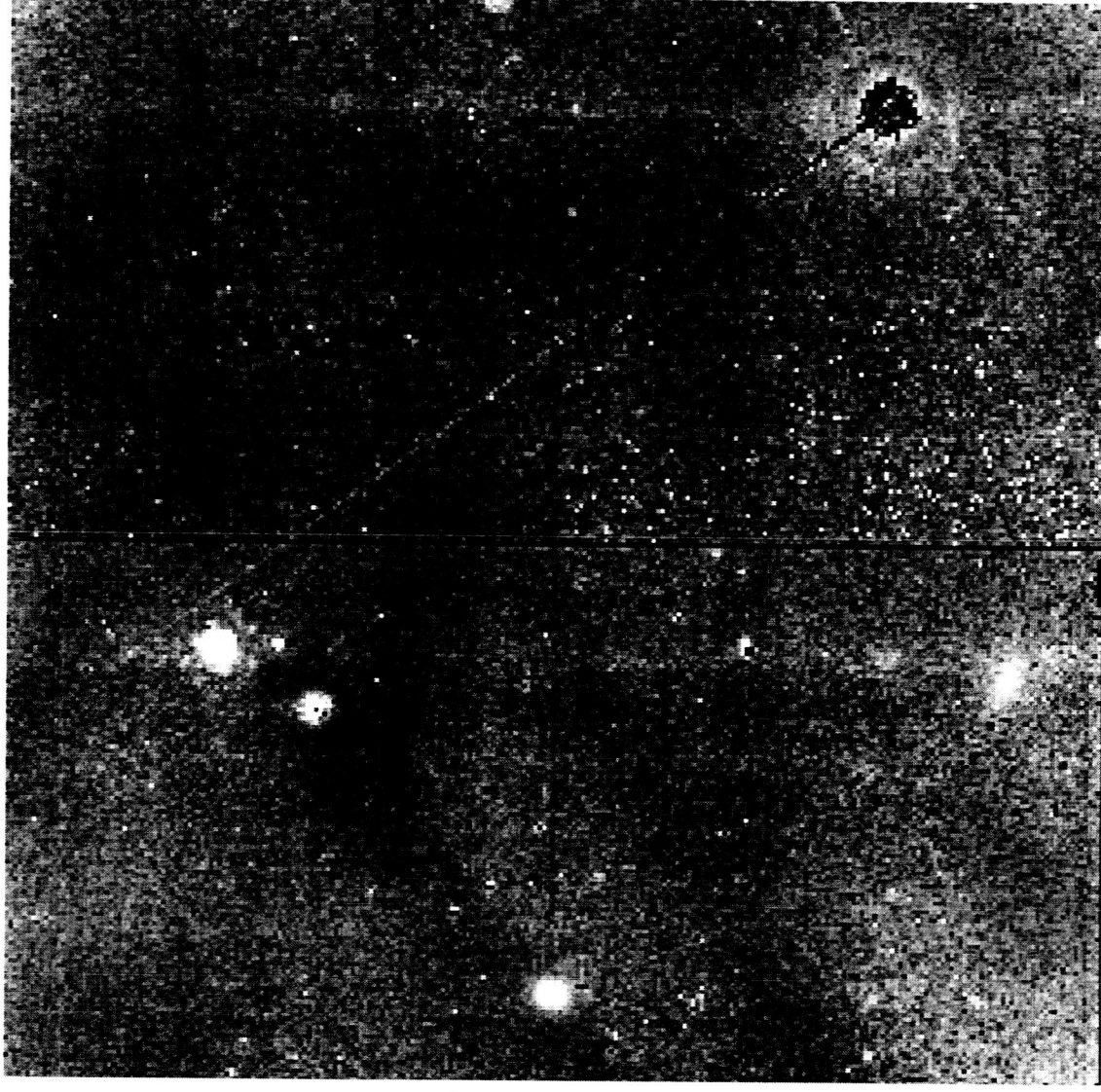
\*NEPP/DTRA/SEE : Evaluation of different MC codes

for space flight applications  
 \*\* JWST : Develop computational methods for IR FPA

# Space Radiation Interactions as Observed by NICMOS

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Figure 2.4



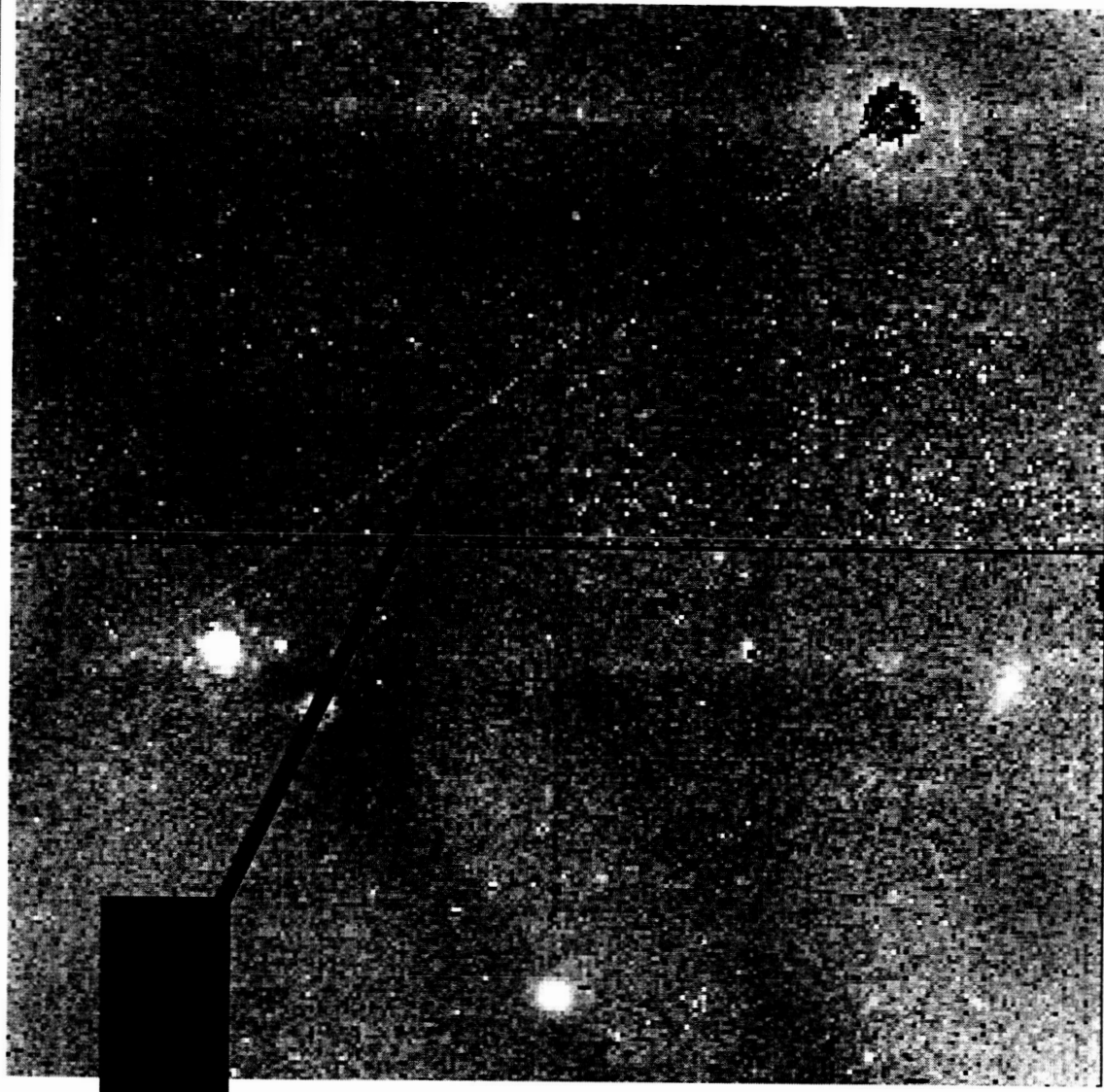
<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>

Presented by Robert Reed, NASA/GSFC at Vanderbilt University

# Space Radiation Interactions as Observed by NICMOS

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Figure 2.4

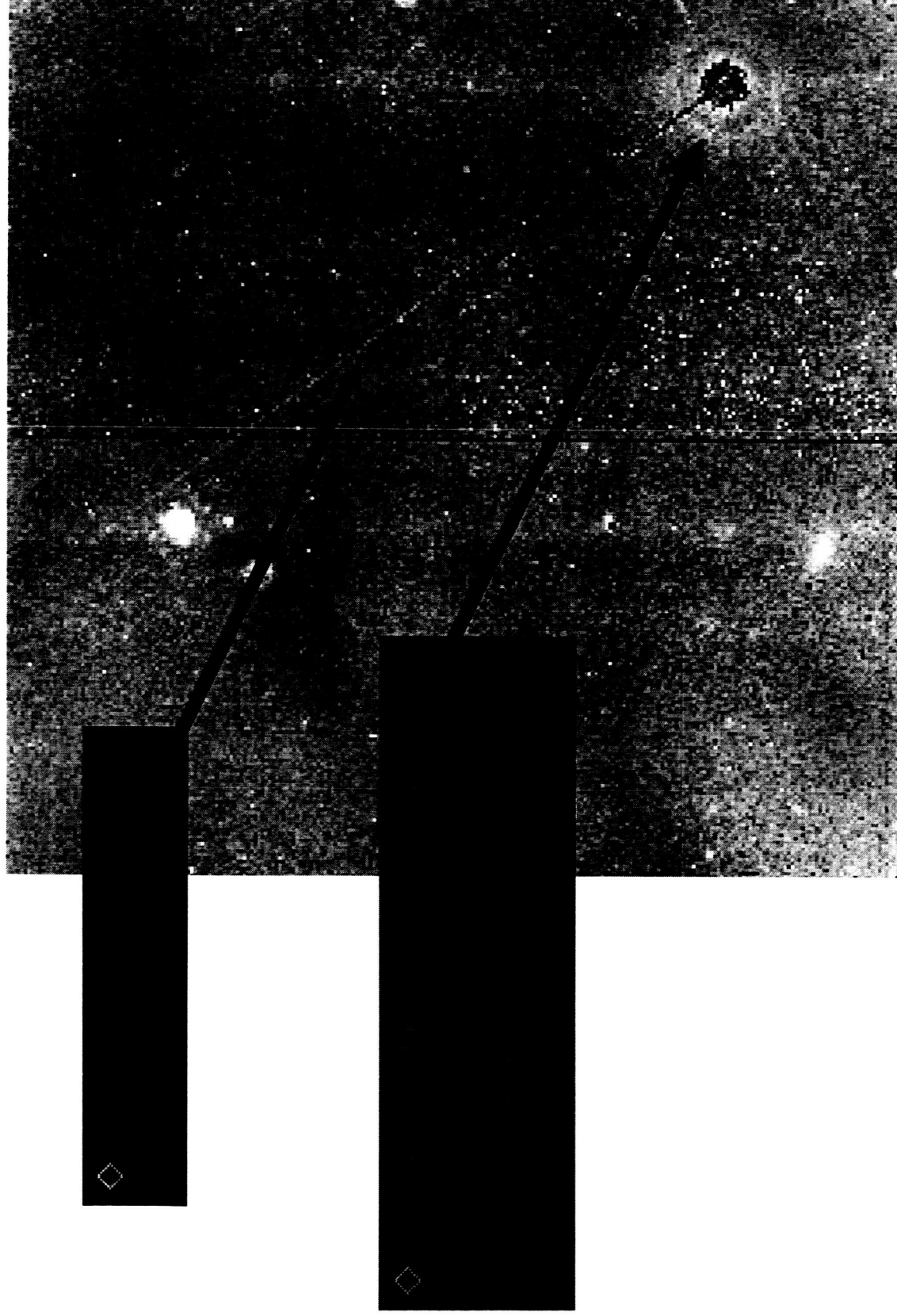




# Space Radiation Interactions as Observed by NICMOS

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Figure 2.4





# Prompt Ionizing Events

Figure 2.4

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## Single Event Effects (SEE)

# Prompt Ionizing Events

Figure 2.4

## Single Event Effects (SEE)

- Direct Ionization

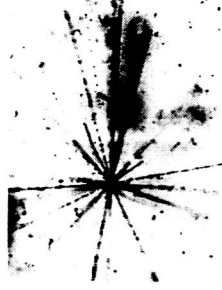
- Typically Heavier Ions ( $Z > 1$ )
- Linear Energy Transfer (LET)
  - Energy per length
- Frequency of the Events in space radiation



Direct

- Indirect Ionization

- Fragments from Nuclear Collision
- Proton Energy
- Frequency of the Events in space radiation



Indirect

*P.J McNulty, Notes from 1990 IEEE Nuclear and Space  
Radiation Effects Conference Short Course*

# Prompt Ionizing Events

Figure 2.4

## Single Event Effects (SEE)

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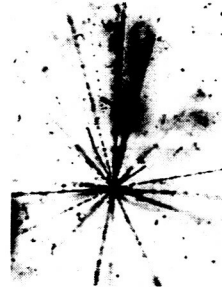
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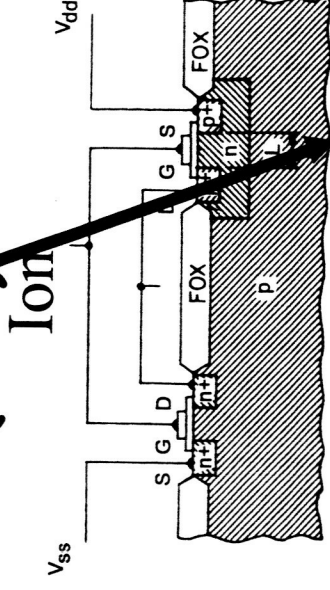
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Indirect

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Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

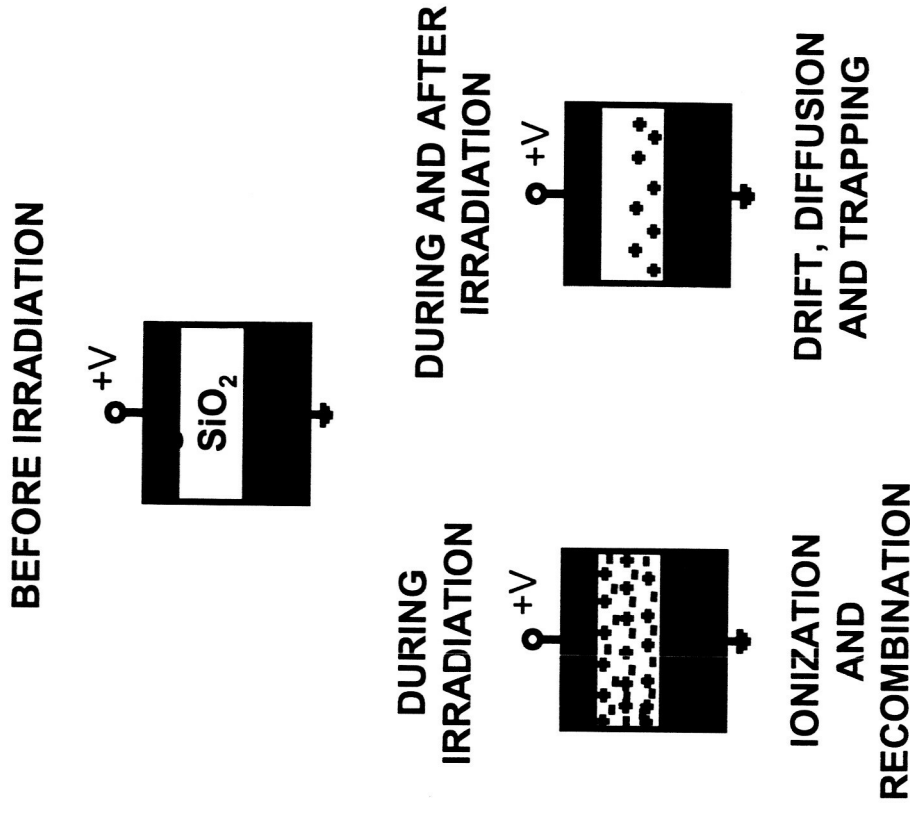
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- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interrupt
- Single Event ...

# Cumulative Degradation for Multiple Ionizing Events

Figure 2.5

## Total Ionizing Dose (TID)

- Permanent damage, some annealing occurs for certain devices
- Can lead to Functional failure



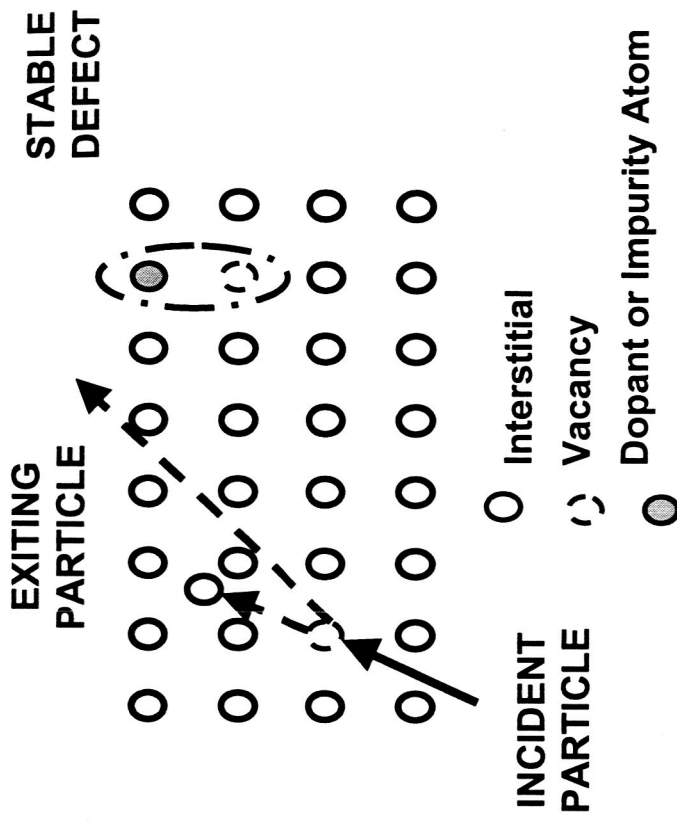
*J.L. Leray, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course*

# Cumulative Degradation and Prompt Response for Non-Ionizing Events

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## Displacement Damage

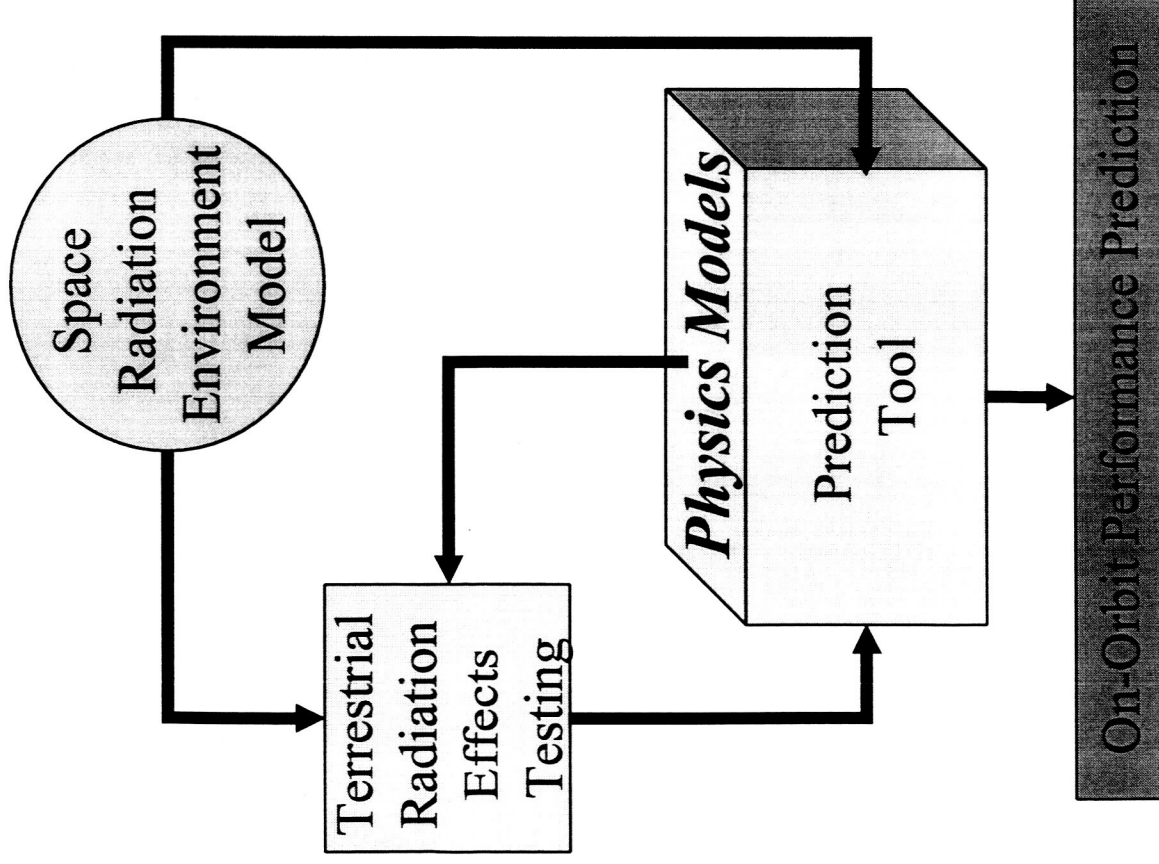
- Cumulative effects that cause device performance degradation
  - Displacement Damage Dose
- Prompt effects causing device performance degradation
- Permanent damage, some annealing occurs for certain devices



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# General On-Orbit Performance Prediction

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- The details of each step in this process depend on the type effect that is being analyzed
  - e.g. prompt response (SEE) will be different than cumulative degradation (TID)

# Applications of Computation Physics

Figure 2.4

- Atomic Interactions
  - Direct Ionization
  - TID
  - SEE
- Interaction with Nucleus
  - Indirect Ionization
  - Nucleus is Displaced
  - SEE
  - Displacement Damage



## Computational Radiation Transport and Interaction Physics (CRTIP)

- NOVICE is the best suited for TID studies\*
  - Adjoint mode monte-carlo
- MCNPX is the best suited for displacement damage studies\*
  - Uses Lindhard energy partitioning
  - Includes elastic scattering
- GEANT4 is the suited for SEE studies\*
  - Most flexible for user modules
- REACT is the suited for SEE studies\*
  - Quasi-device physics code

\* These results will change as we review other codes and as these codes improve



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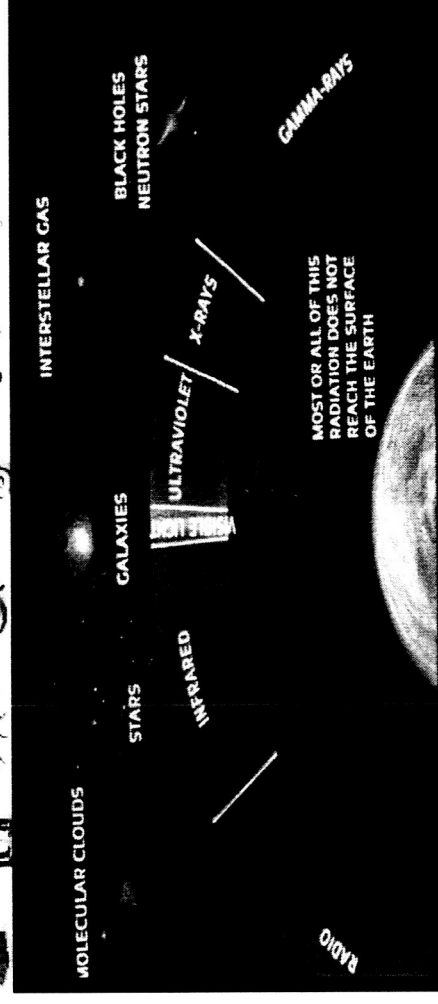
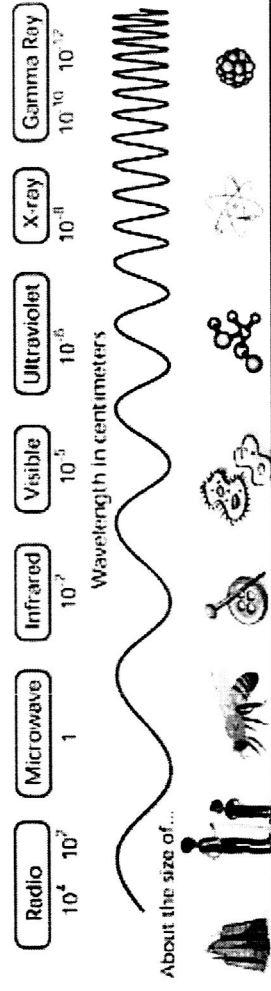
# **Computational Radiation Transport and Interaction Physics**

## **James Webb Space Telescope**

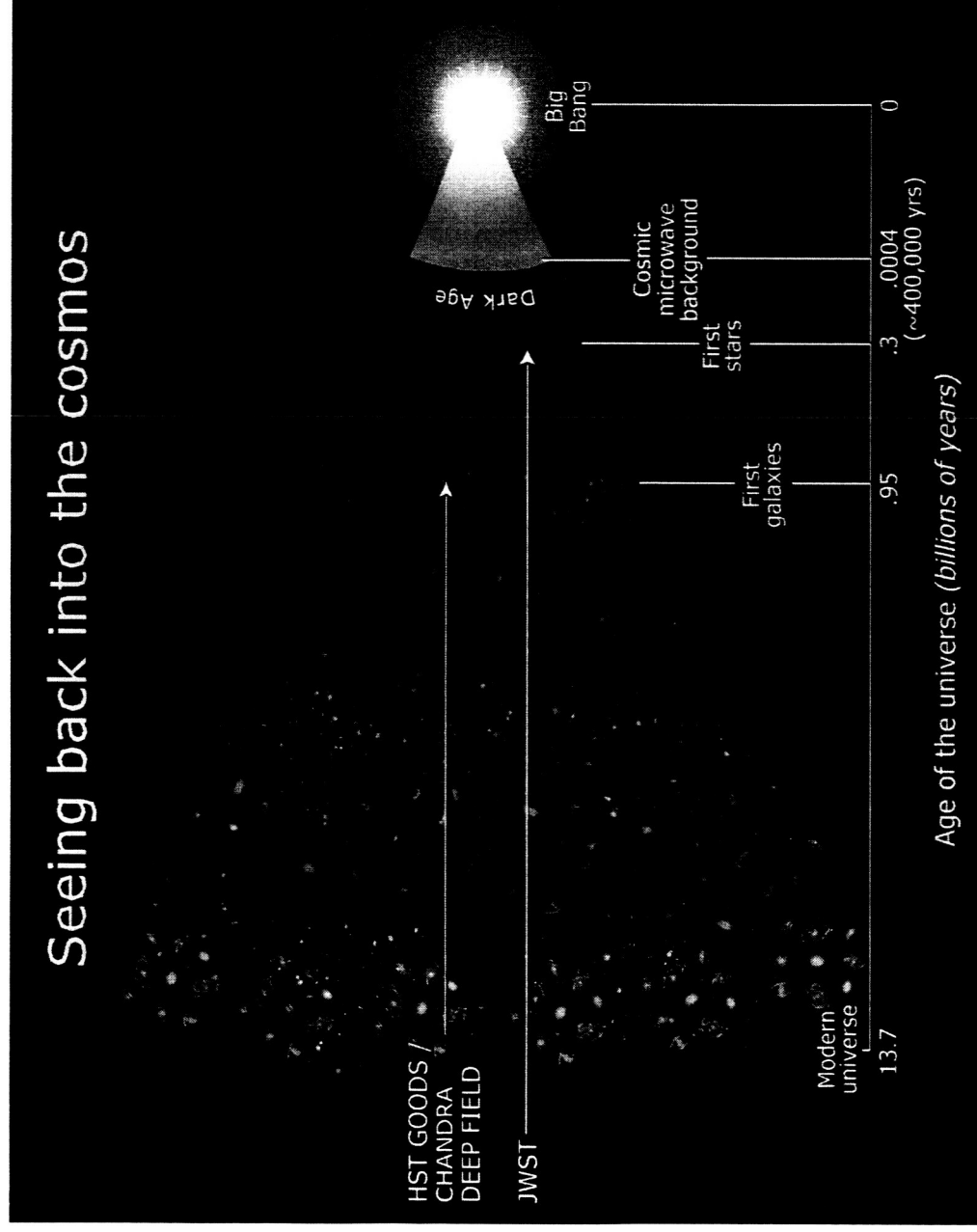


## Low Noise Quantitative Detection Across the Spectrum

- Ground-based Radio Astronomy
- Microwave looks at the Cosmic Microwave Background
  - COBE, FIRS, WMAP
- Mid to long wave IR (>5 mm)
  - SIRTIF, JWST
- Near Infrared
  - HST - WFC3 & NICMOS
- Visible (panchromatic)
  - HST - WFPC2, ACS, WFC3
- Near uV to VuV (solar phys)
  - SOHO, SDO, STEREO
- X-ray
  - CHANDRA, XMM-Newton
- $\gamma$ -ray
  - GRO, GLAST, RHESSI
- Gravity wave - Laser Interferometer Space Antenna - LISA

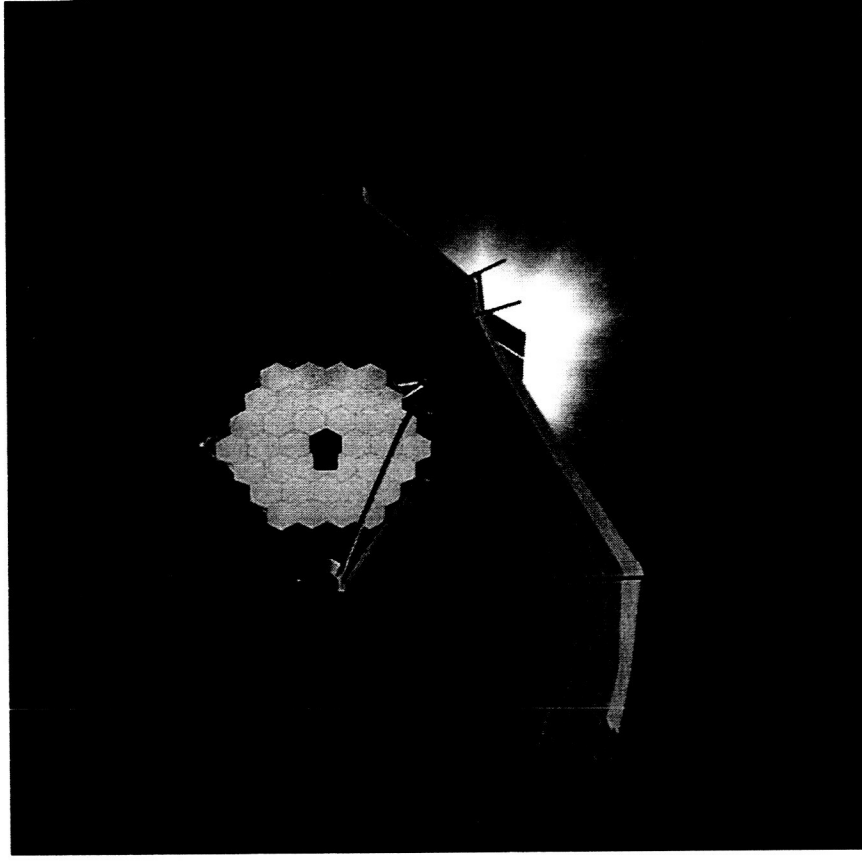
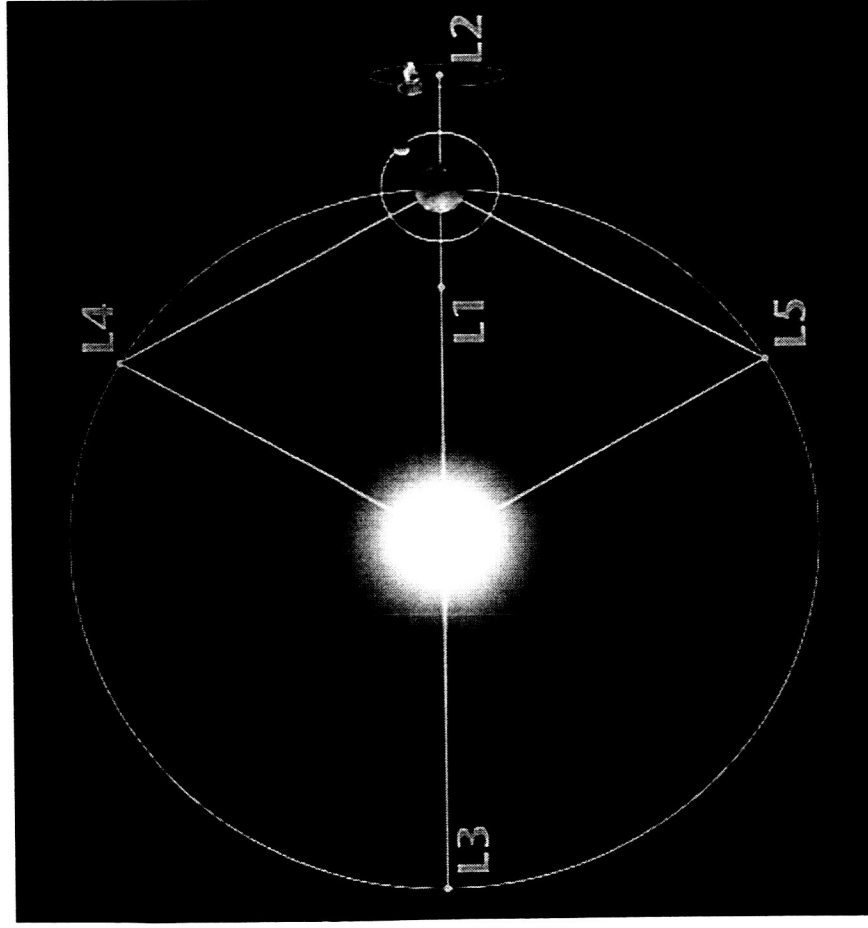


# James Webb Space Telescope



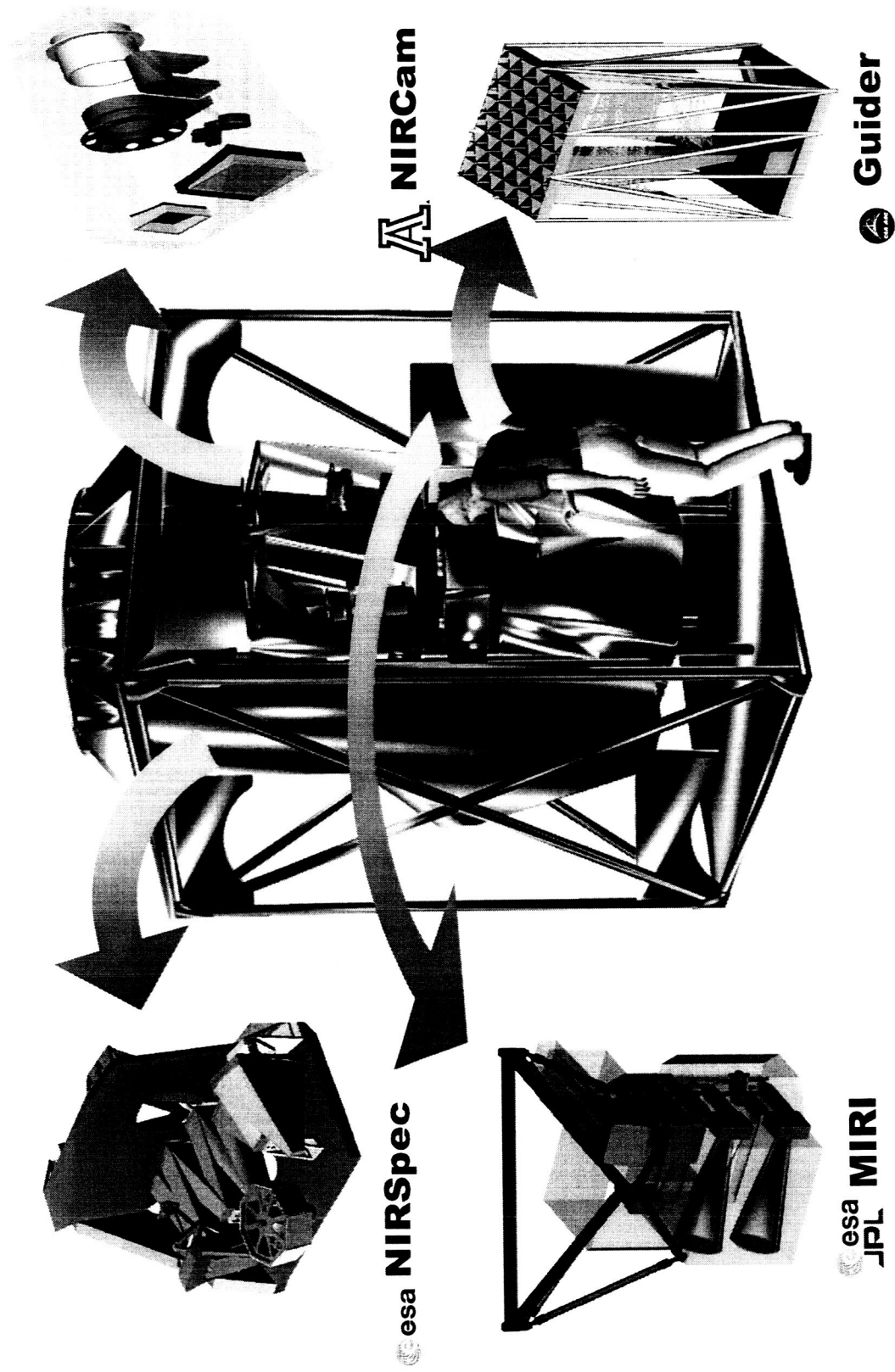
# James Webb Space Telescope

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# James Webb Space Telescope

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# JWST IR Focal Plane Array Detectors

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- REAG along with JWST team is currently working to assess radiation effects in HgCdTe Detector Arrays
  - Radiation induced transient (Prompt Response)
    - Low noise requirement: 3-10 electrons for 1000 sec integration time
  - Permanent degradation (TID and Displacement Damage)
    - Requirement of >90% good pixel at end of mission

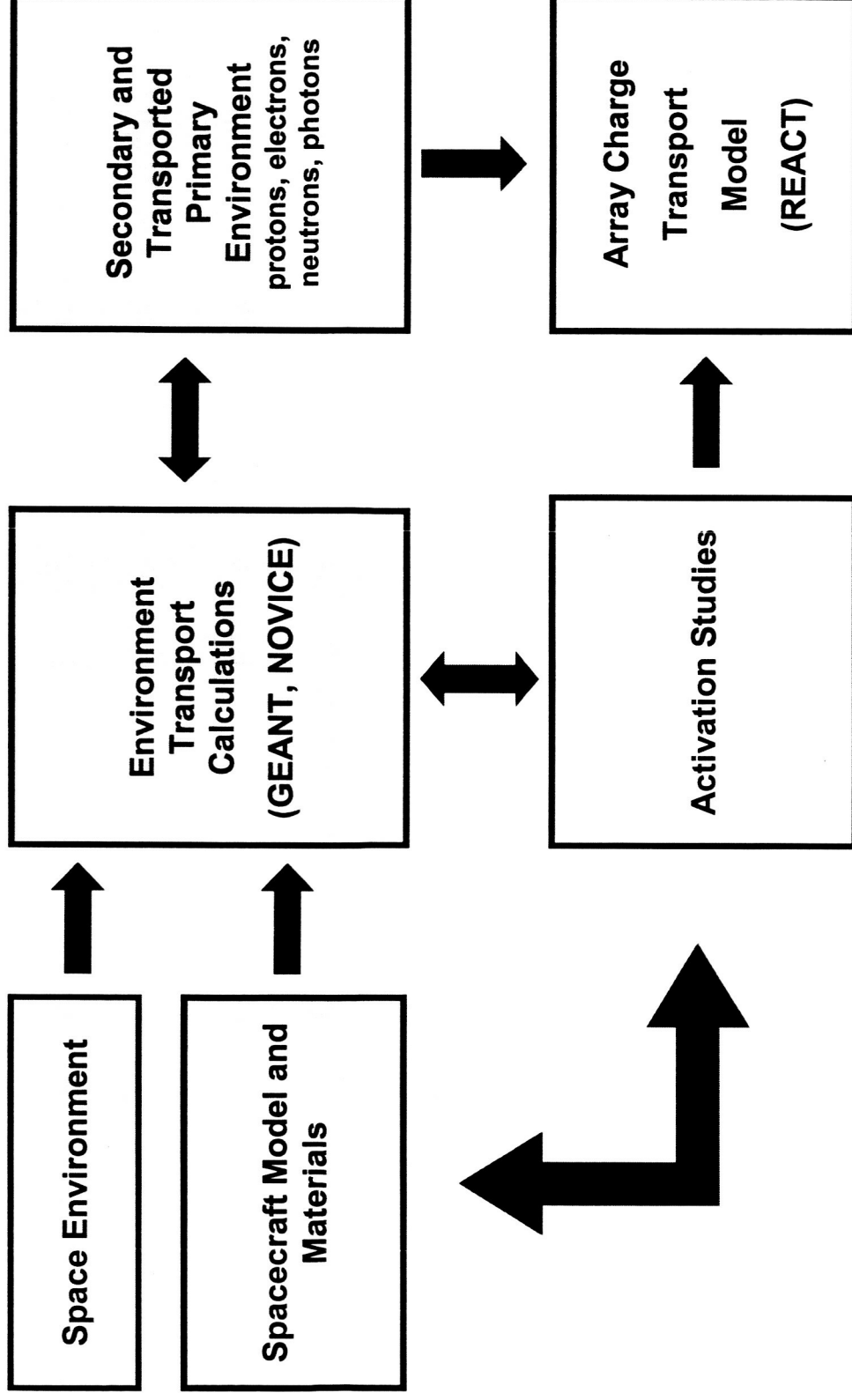
## FPA Transient Response Model

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- Goal of analysis is to predict FPA response to incident energetic particles (protons, heavy ions, electrons)
  - Pixel-by-pixel charge contamination from particle hit
  - Quantify crosstalk and multi-pixel hits
- Source term is external radiation environment and transport through material surrounding FPA
  - Includes primary and secondary environment
  - Includes decay of activated material and inherent radioactivity
- Use detailed FPA charge collection model (REACT) to allocate charge to each pixel
- Output is simulation of FPA operation in JWST particle environment (e.g., FITS file)

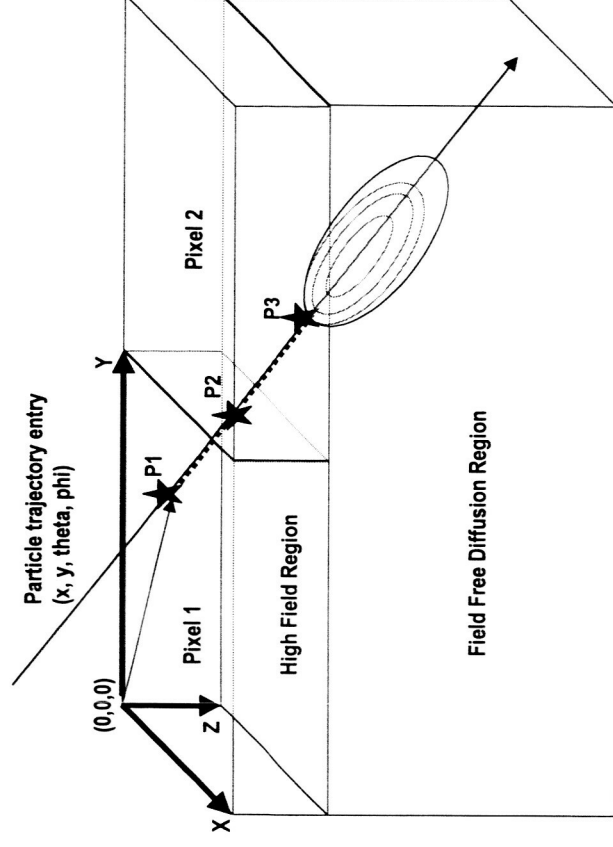
## General Modeling Approach

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## Array Charge Collection Model (REACT)

- Initial line source of minority carrier distribution based on particle LET and trajectory
- Drift and diffusion charge collection models applied depending on particle location
- Charge carrier history ends when either collected or recombined
- Charge distributed to pixels across array in accordance with drift and diffusion
- Output is pulse height distributions, crosstalk characterization, FITS files, etc.

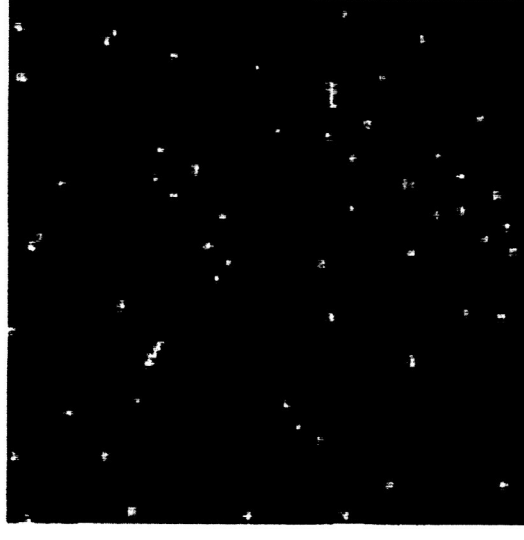
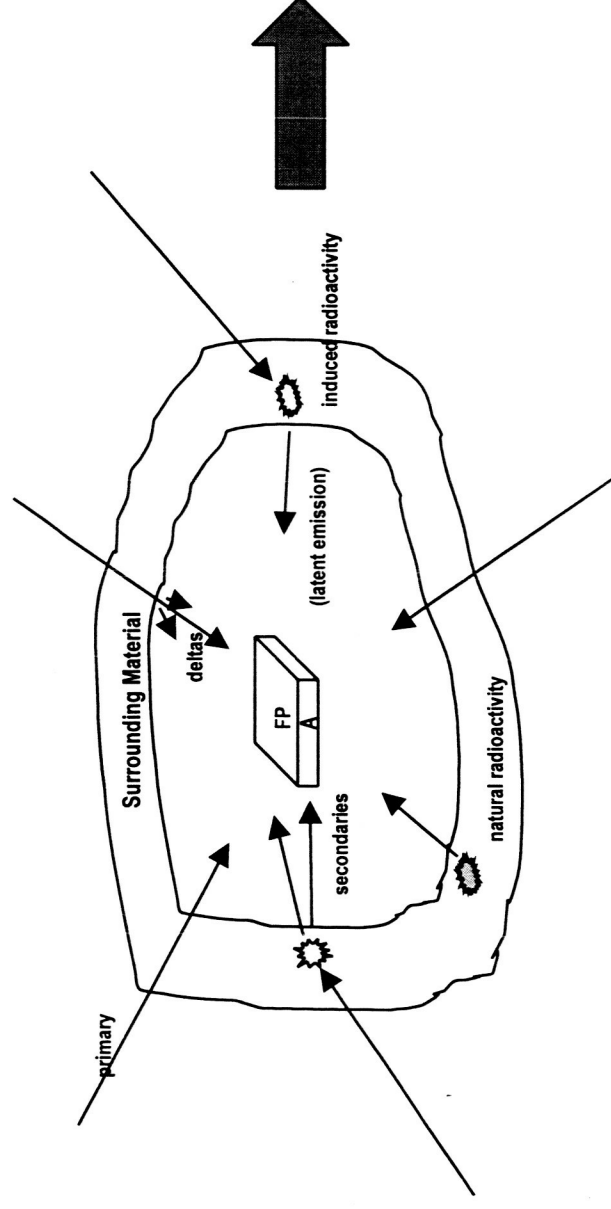




# Future Direction for Modeling on On-Orbit Prompt Response

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- Predict the environment at the FPA using GEANT4, MCNPX, NOVICE, and EASY
  - Requires detailed information about the spacecraft structure around the FPA
- Determine the response of the FPA using REACT



# Roadmap

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- Collaborators:
  - NASA/GSFC
  - Vanderbilt University
- Also coordinating with ESA efforts
- Near Term Goals
  - Compare GEANT4 results to other models
    - Ion track structure in Silicon
    - Proton-reaction recoil nuclei distributions
  - Develop CRTIP techniques to be capable of predicting heavy ion and proton SEE rates using existing models
  - Convert NASA's drift and diffusion modeling routines (called REACT) to be compatible with OOP
  - Proof of concept for establishing a parallel processing in Geant4
    - Vanderbilt has access to >120 node Cluster of >2GHz machines
  - Develop collaboration with Geant4 development team

# Roadmap: Intermediate and Long Term Goals

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- Intermediate Goals
  - Develop Geant4 routine capable of predicting SEEs using REACT
  - Develop user define modules for using Geant4/REACT for SEEs in fiber link / optocoupler and benchmark against available radiation test data
    - This module will be available to the public in a user-friendly format
  - Develop full parallel processing capability for Geant4
- Long Range Goals
  - Development of user define Geant4/REACT modules for other technologies
    - SOI/SOS
    - SiGe and others
  - Develop capability of using Geant4 with Detailed Device Physics simulation for predicting circuit response
  - Continue to develop user define modules for using Geant4/REACT Making them available to the public in a user-friendly format

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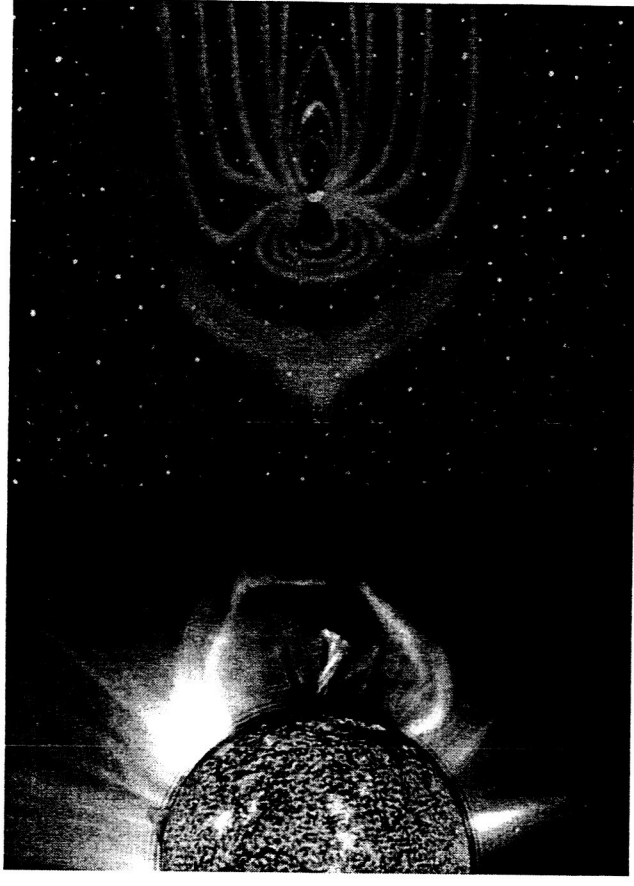
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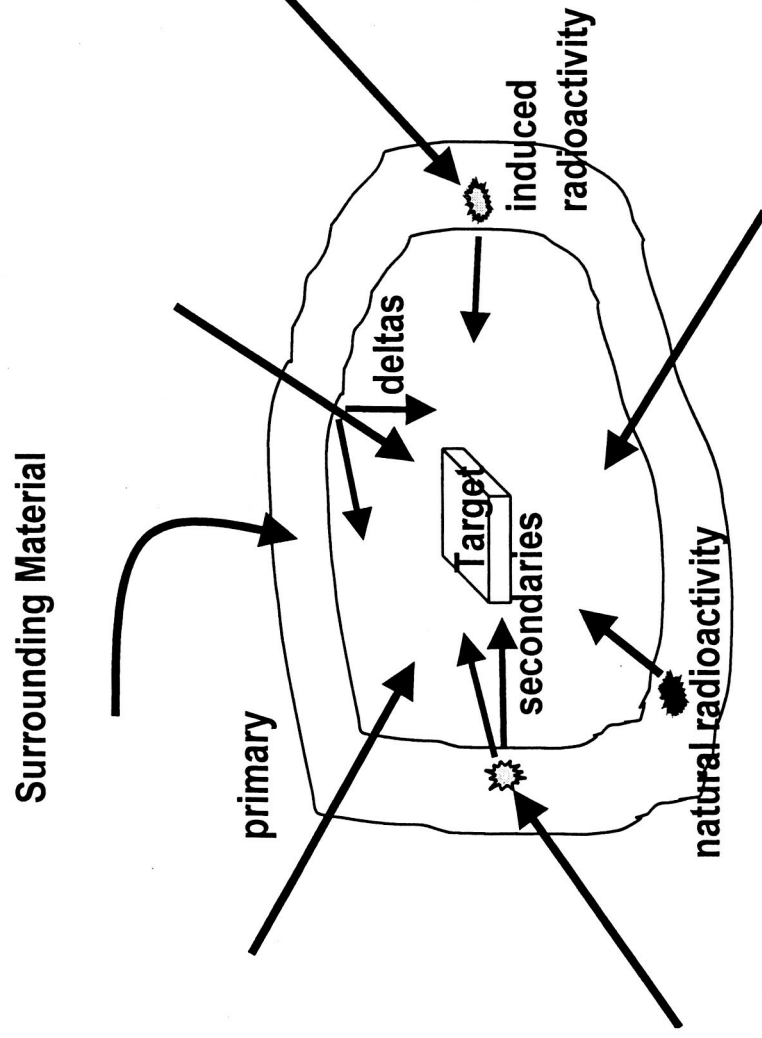
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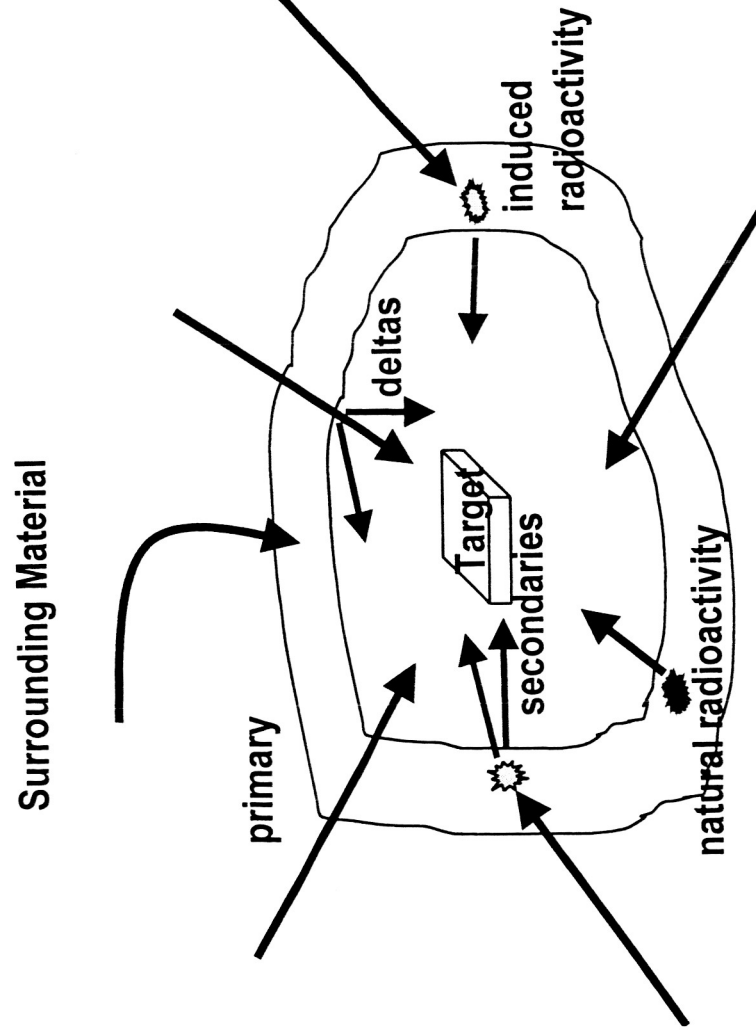


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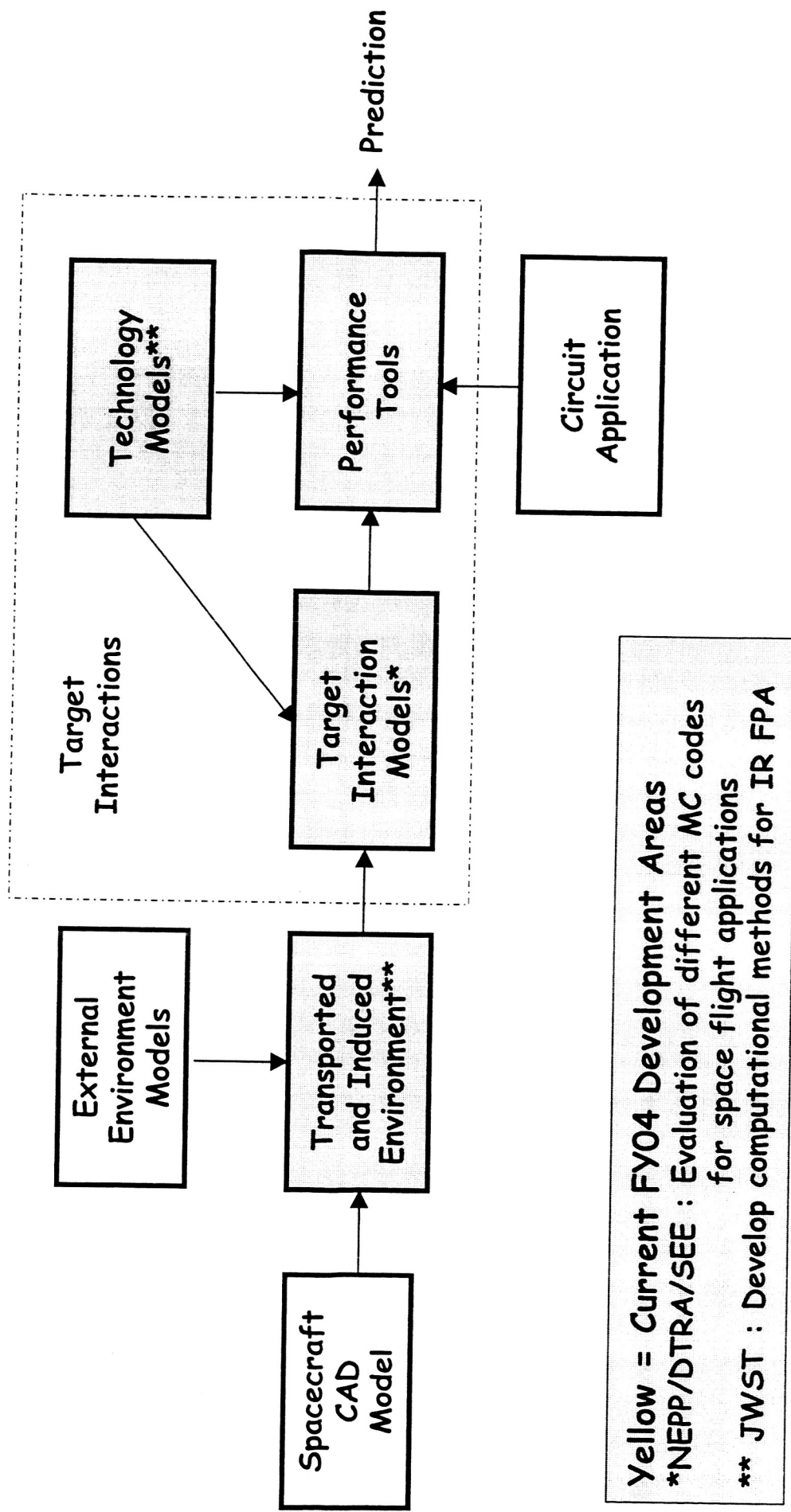


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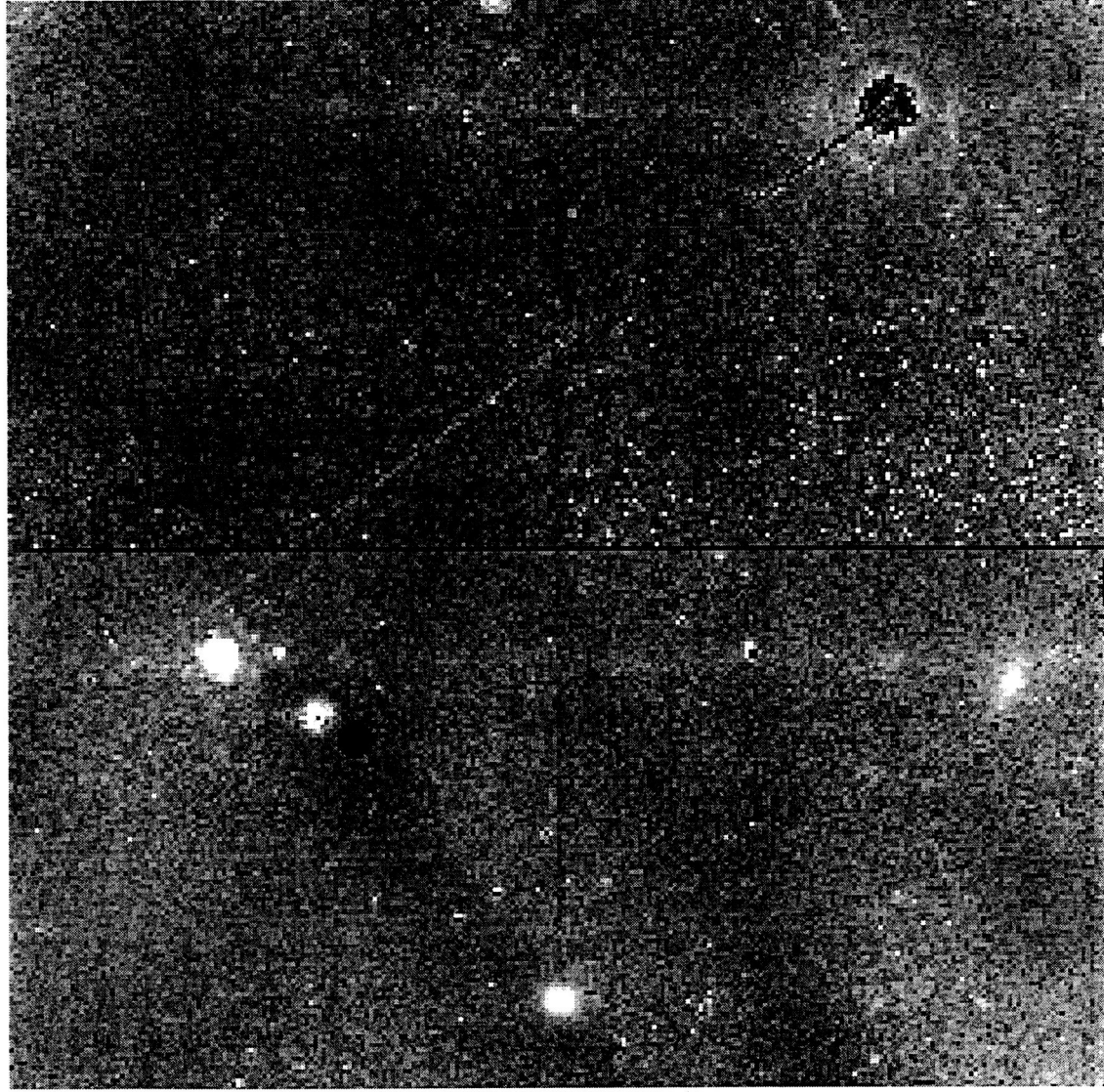
# Space Computational Radiation Interaction Performance Tools (SCRIPT)



# Space Radiation Interactions as Observed by NICMOS

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Figure 2.4

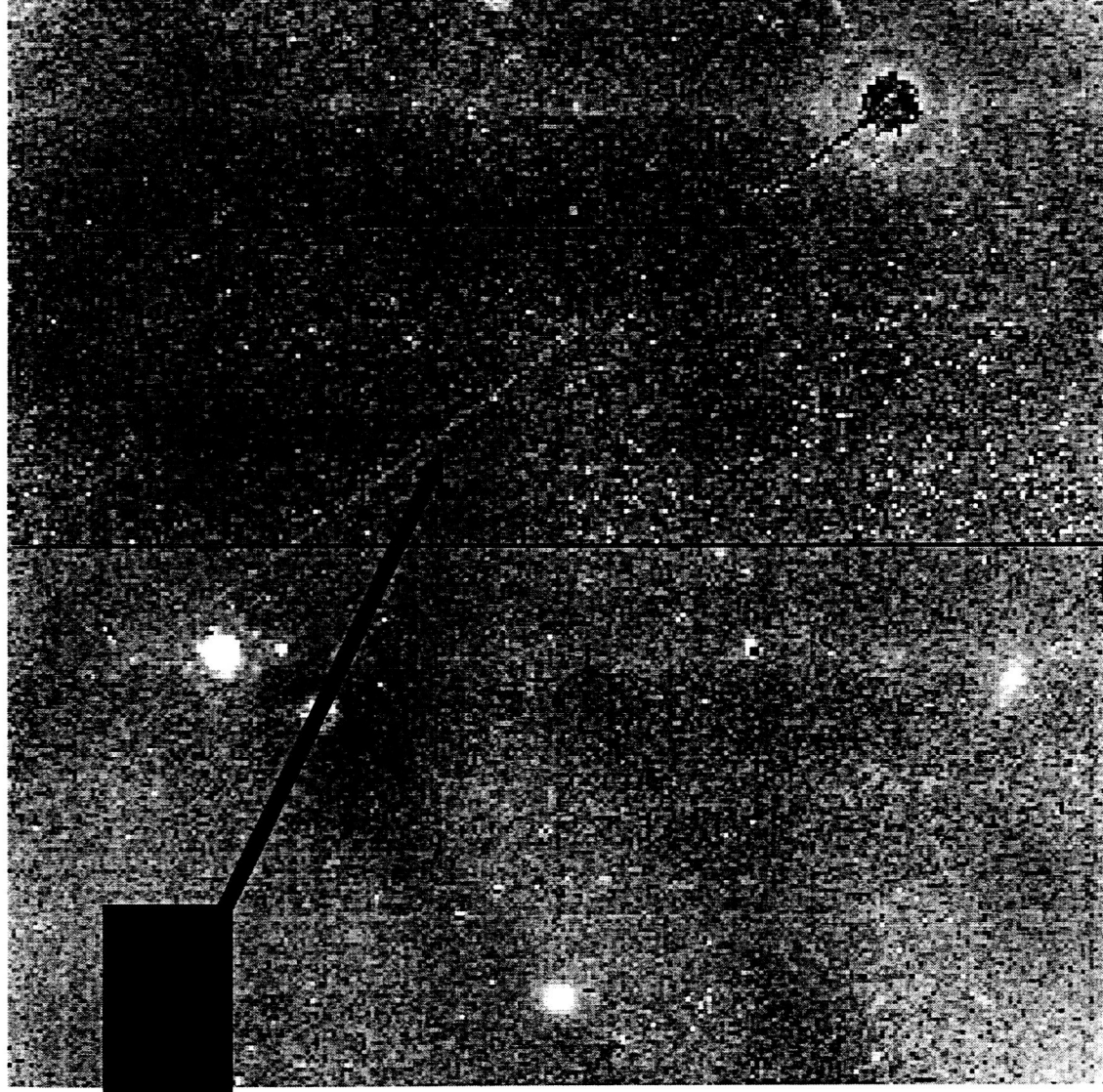


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May, 11 2004

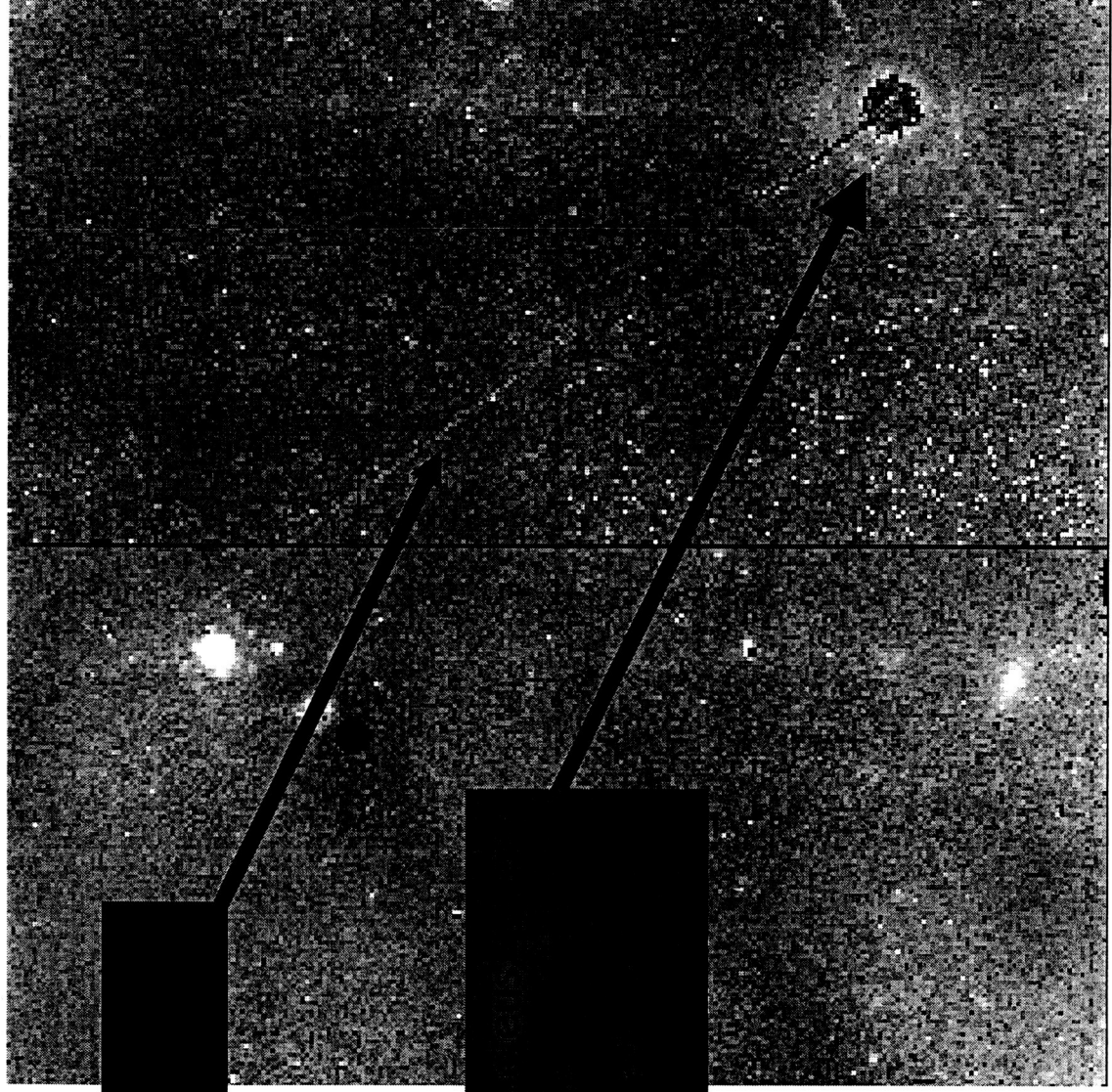
Presented by Robert Reed, NASA/GSFC at Vanderbilt University



# Space Radiation Interactions as Observed by NICMOS

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# Prompt Ionizing Events

Figure 2.4

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## Single Event Effects (SEE)

# Prompt Ionizing Events

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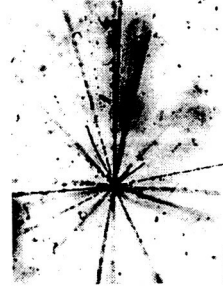
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Indirect

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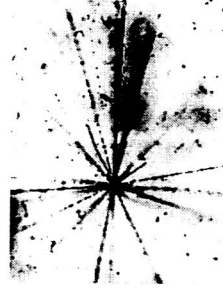
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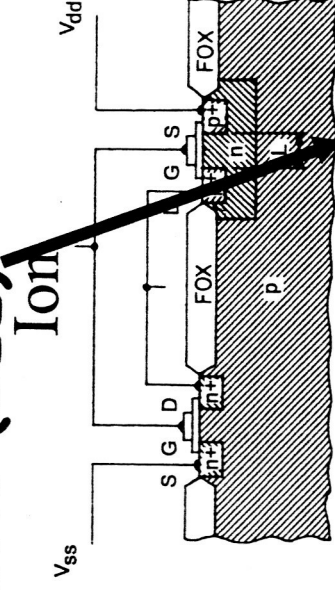
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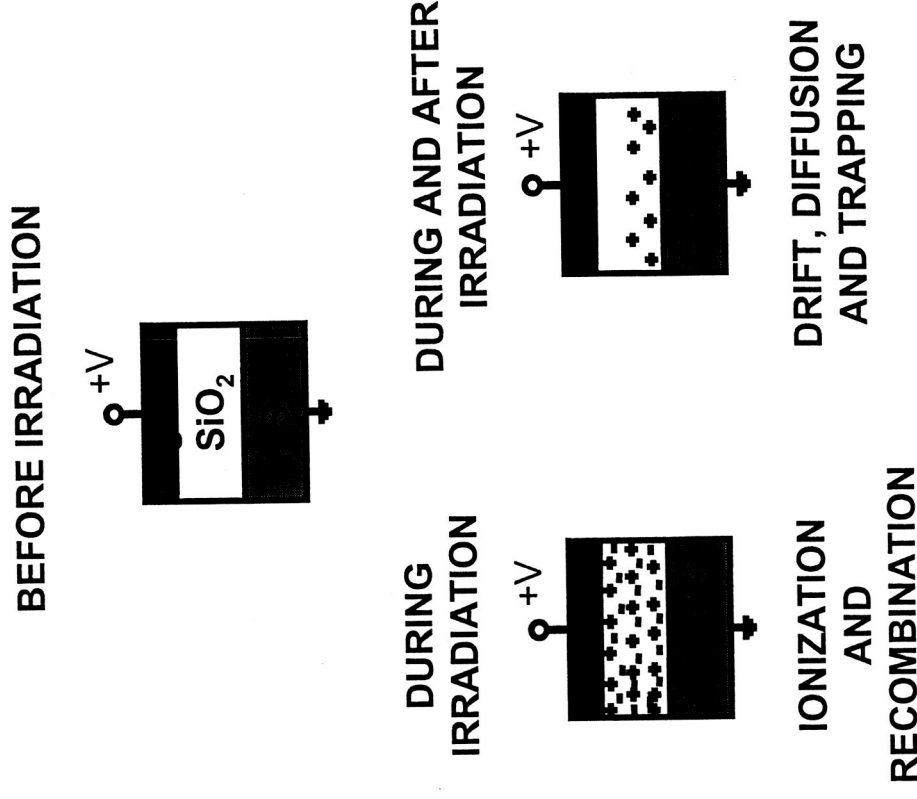


# Cumulative Degradation for Multiple Ionizing Events

Figure 2.5

## Total Ionizing Dose (TID)

- Permanent damage, some annealing occurs for certain devices
- Can lead to Functional failure



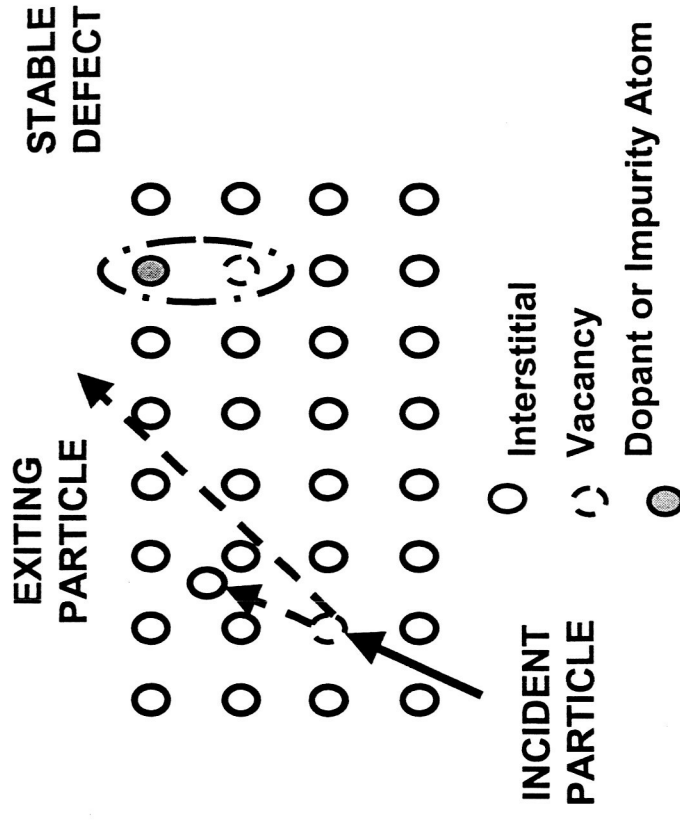
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# Cumulative Degradation and Prompt Response for Non-Ionizing Events

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## Displacement Damage

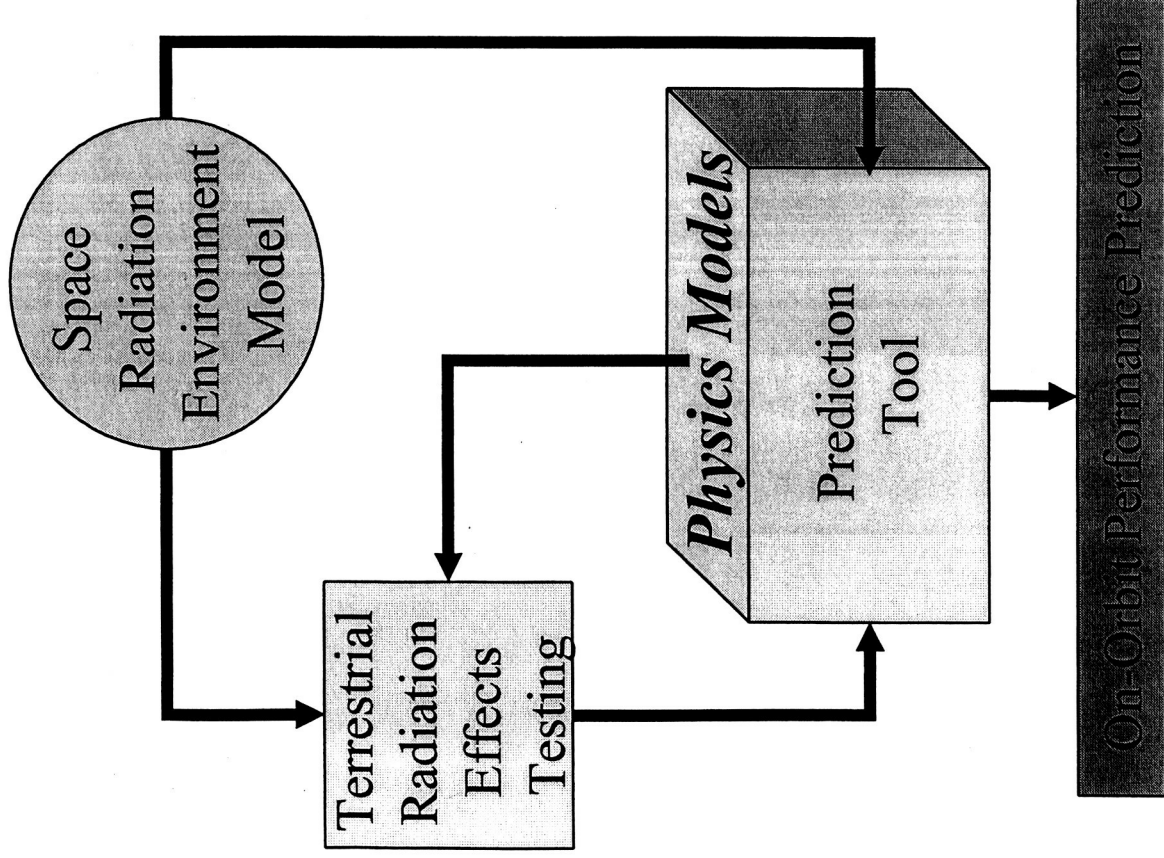
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  - Displacement Damage Dose
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# General On-Orbit Performance Prediction

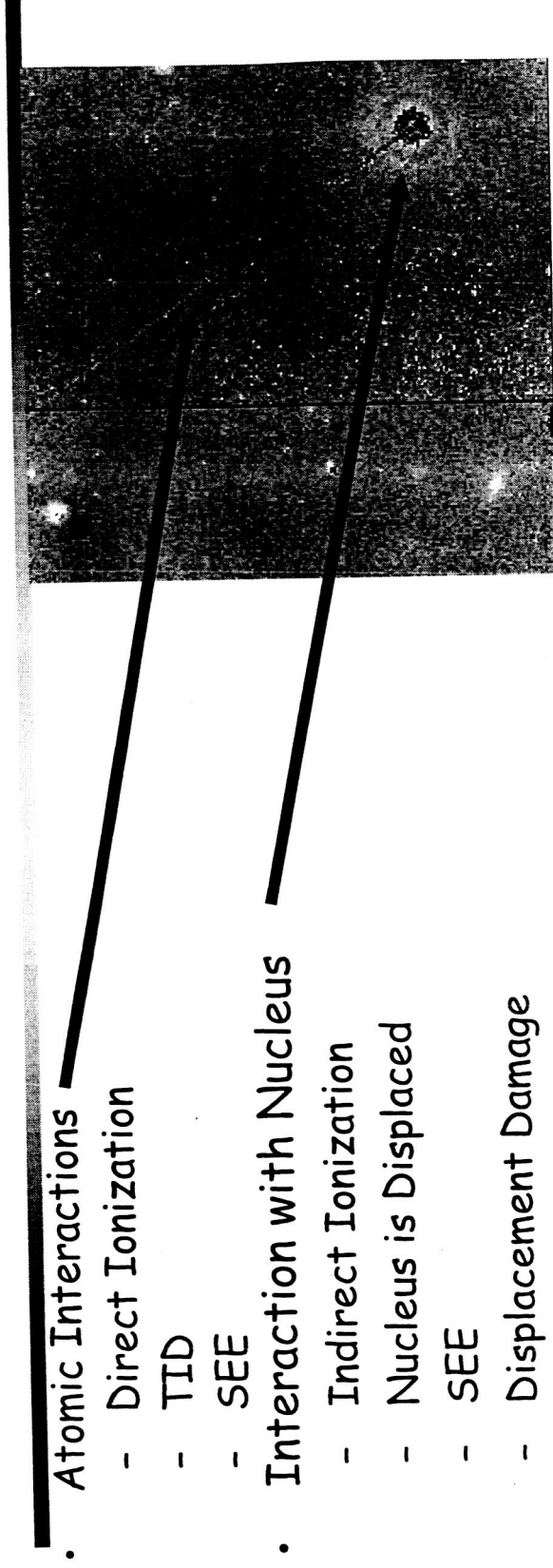
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- The details of each step in this process depend on the type effect that is being analyzed
  - e.g. prompt response (SEE) will be different than cumulative degradation (TID)

# Applications of Computation Physics

Figure 2.4



## Computational Radiation Transport and Interaction Physics (CRTIP)

- NOVICE is the best suited for TID studies\*
- MCNPX is the best suited for displacement damage studies\*
  - Adjoint mode monte-carlo
  - Uses Lindhard energy partitioning
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- GEANT4 is the suited for SEE studies\*
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# **Computational Radiation Transport and Interaction Physics**

## **James Webb Space Telescope**

# Low Noise Quantitative Detection Across the Spectrum

- **Ground-based Radio Astronomy**

- **Microwave looks at the Cosmic Microwave Background**

- COBE, FIRS, WMAP

- **Mid to long wave IR (>5 mm)**

- SIRTf, JWST

- **Near Infrared**

- HST - WFC3 & NICMOS

- **Visible (panchromatic)**

- HST - WFPC2, ACS, WFC3

- **Near uV to VuV (solar phys)**

- SOHO, SDO, STEREO

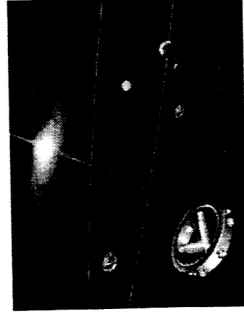
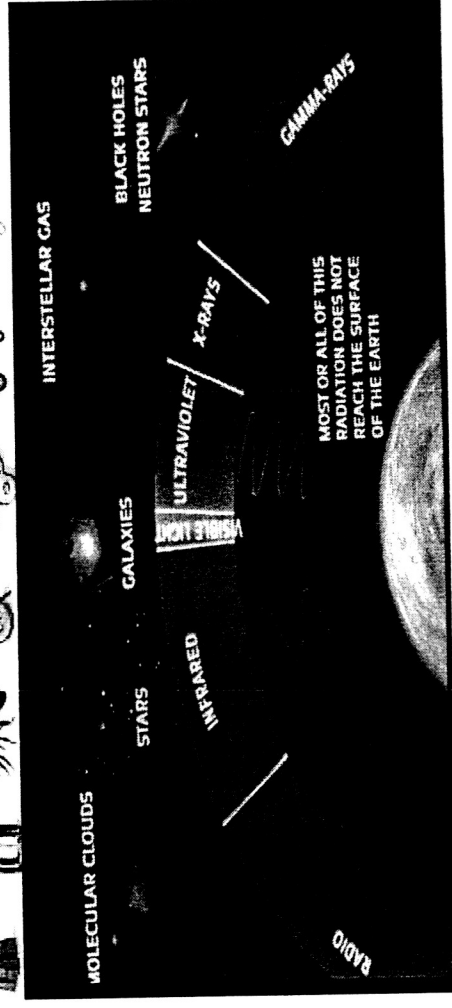
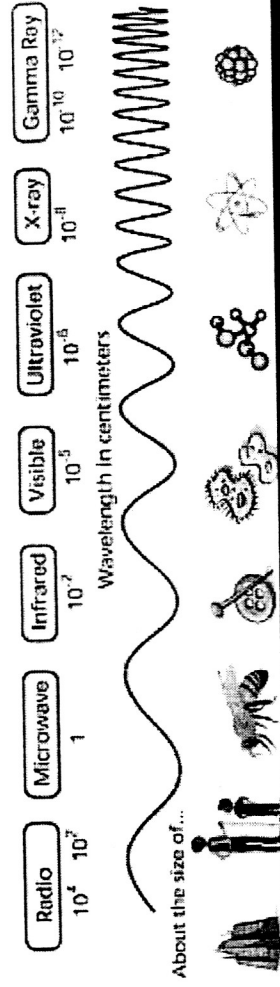
- **X-ray**

- CHANDRA, XMM-Newton

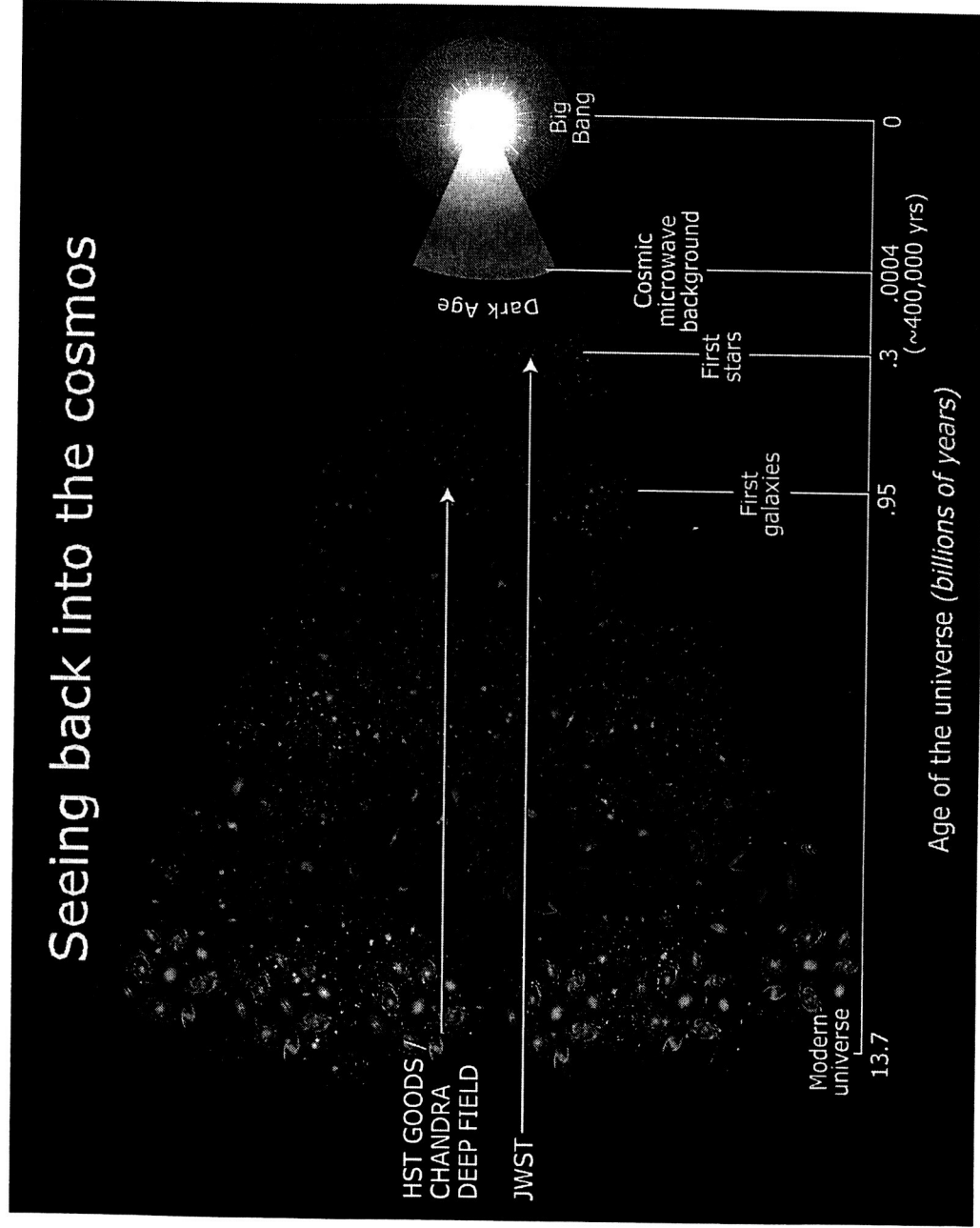
- **$\gamma$ -ray**

- GRO, GLAST, RHESSI

- **Gravity wave - Laser Interferometer Space Antenna - LISA**

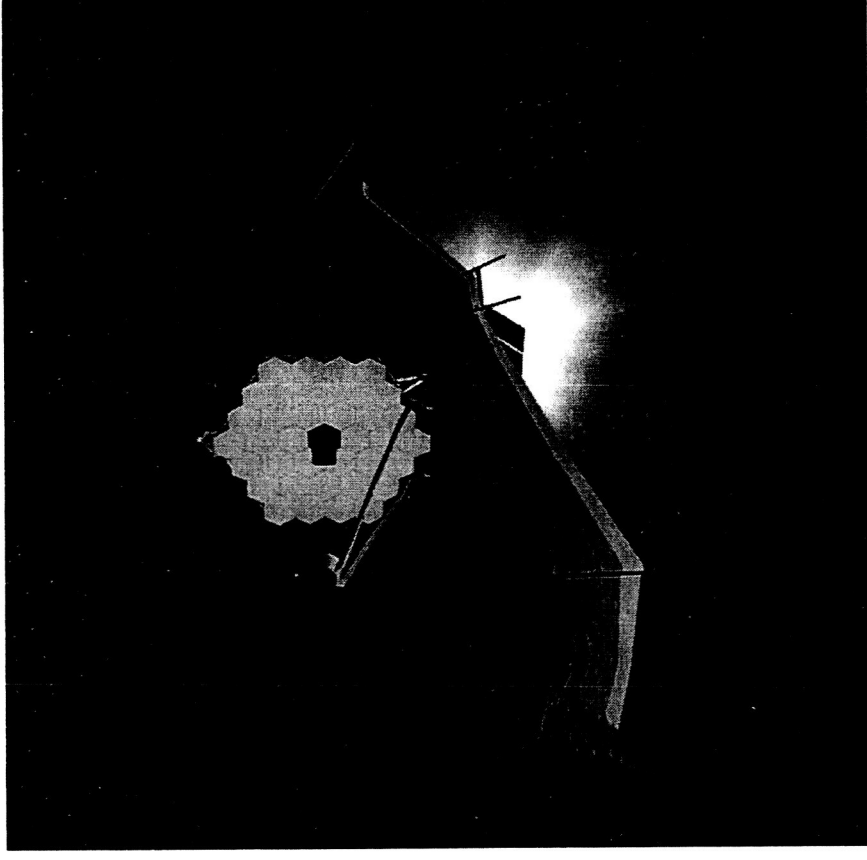
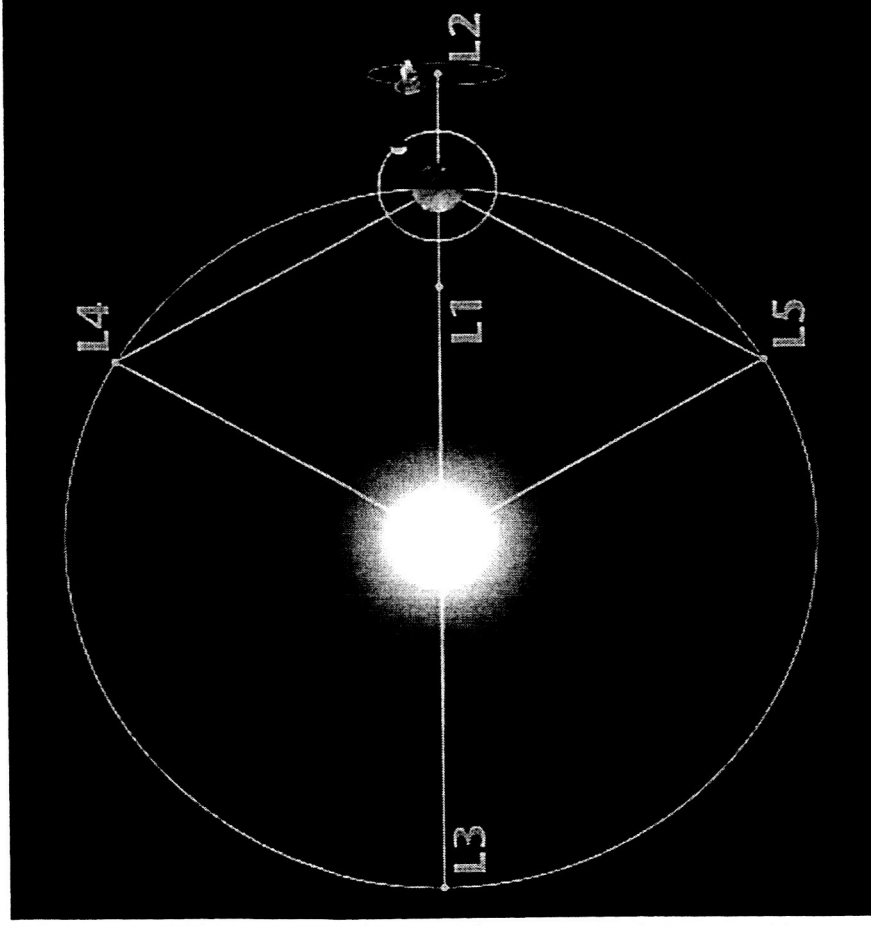


# James Webb Space Telescope



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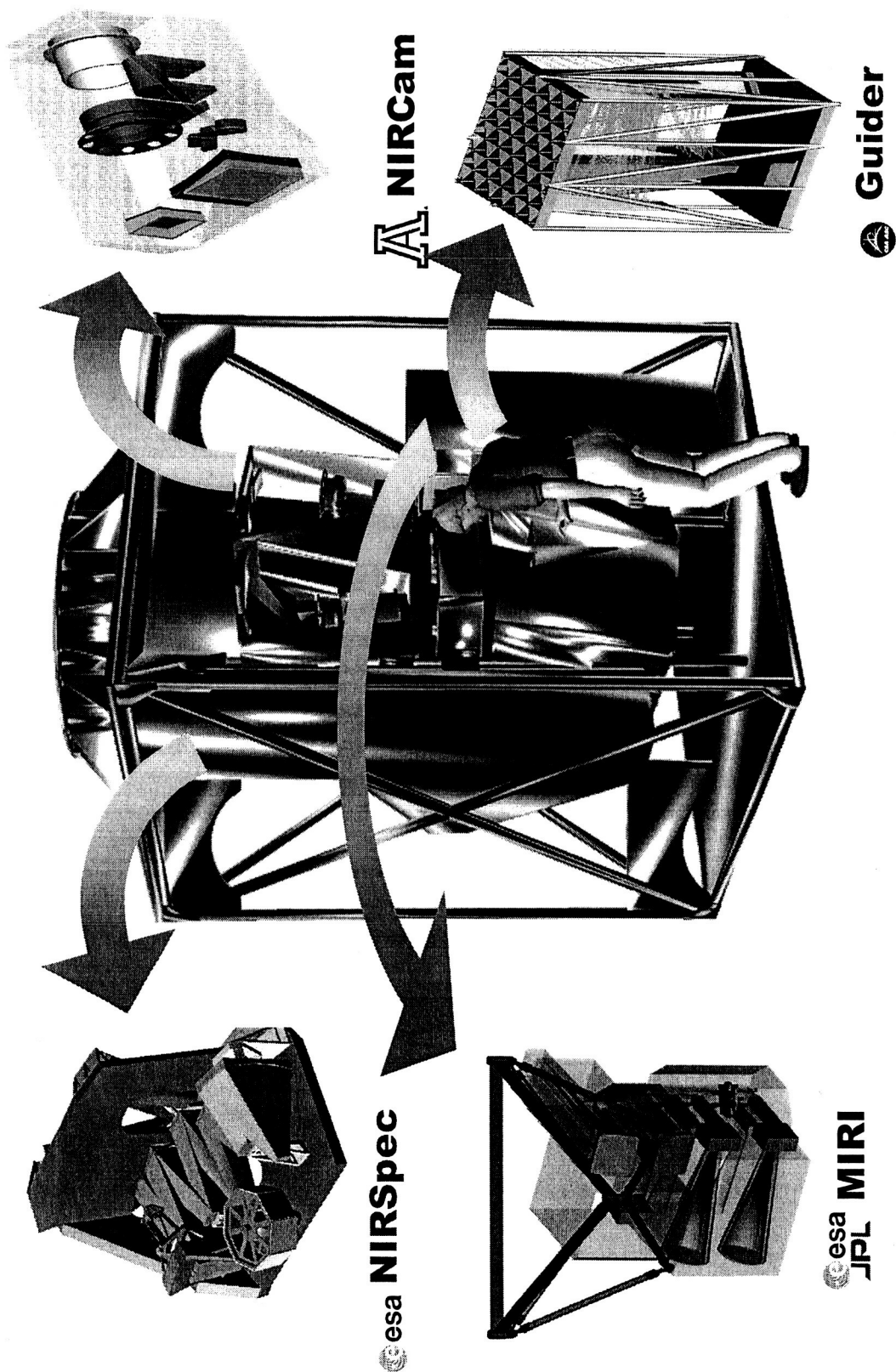
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# James Webb Space Telescope

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# JWST IR Focal Plane Array Detectors

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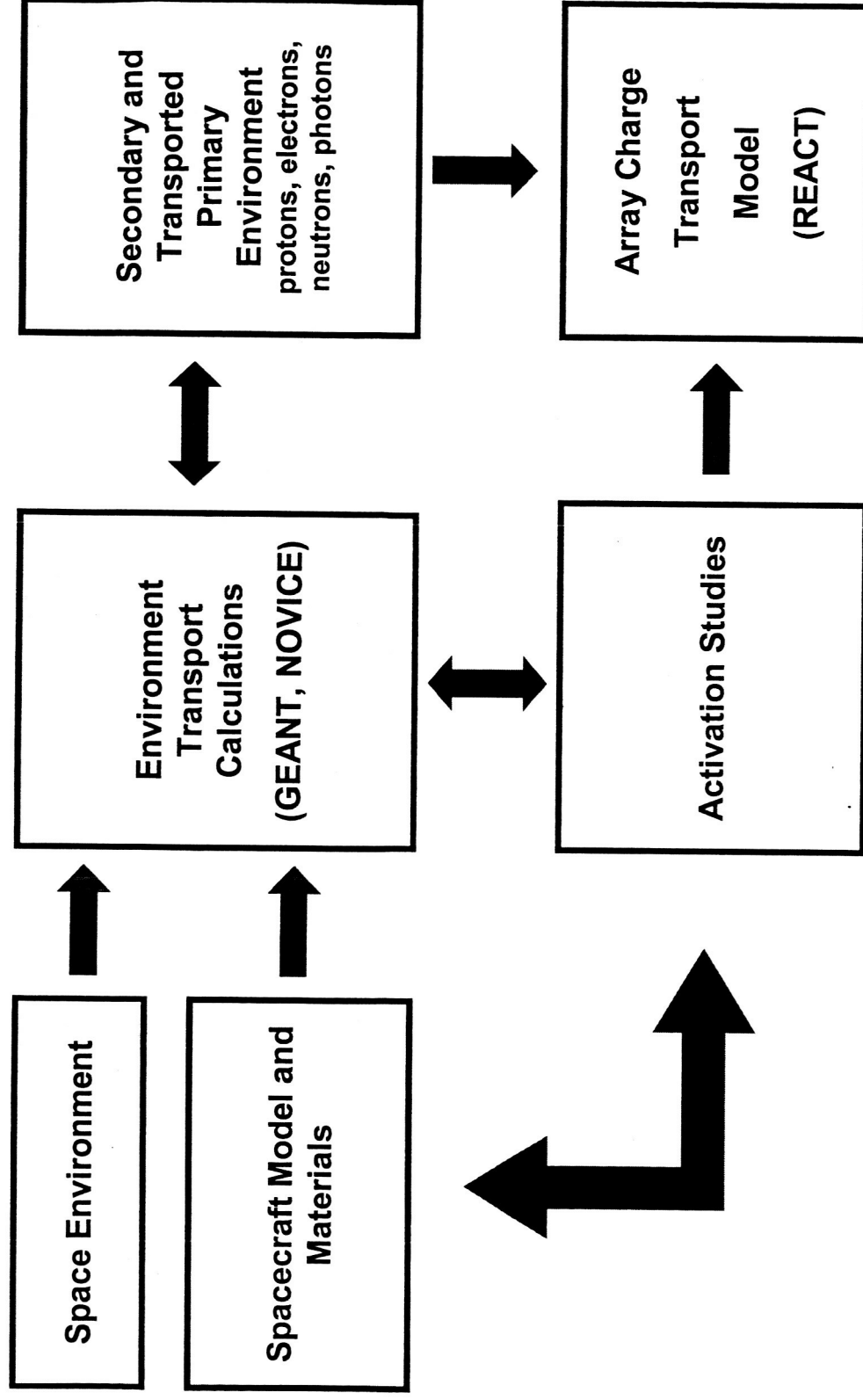
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  - Radiation induced transient (Prompt Response)
    - Low noise requirement: 3-10 electrons for 1000 sec integration time
  - Permanent degradation (TID and Displacement Damage)
    - Requirement of >90% good pixel at end of mission

## **FPA Transient Response Model**

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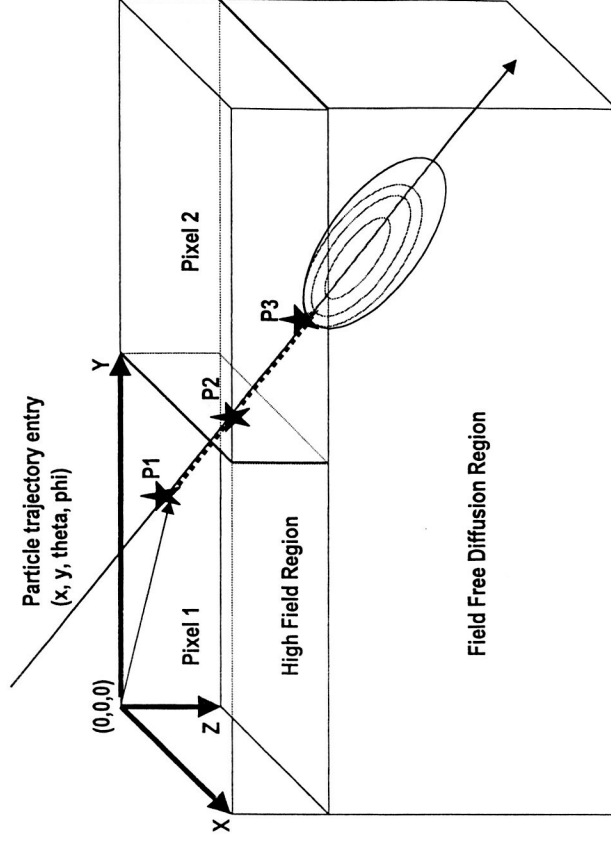
- Goal of analysis is to predict FPA response to incident energetic particles (protons, heavy ions, electrons)
  - Pixel-by-pixel charge contamination from particle hit
  - Quantify crosstalk and multi-pixel hits
- Source term is external radiation environment and transport through material surrounding FPA
  - Includes primary and secondary environment
  - Includes decay of activated material and inherent radioactivity
- Use detailed FPA charge collection model (REACT) to allocate charge to each pixel
- Output is simulation of FPA operation in JWST particle environment (e.g., FITS file)

# General Modeling Approach



## Array Charge Collection Model (REACT)

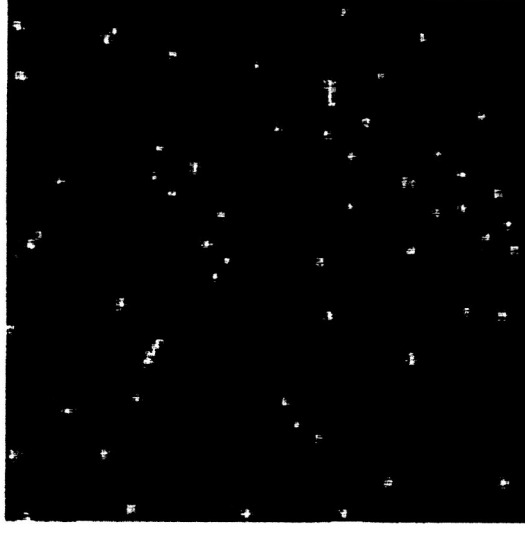
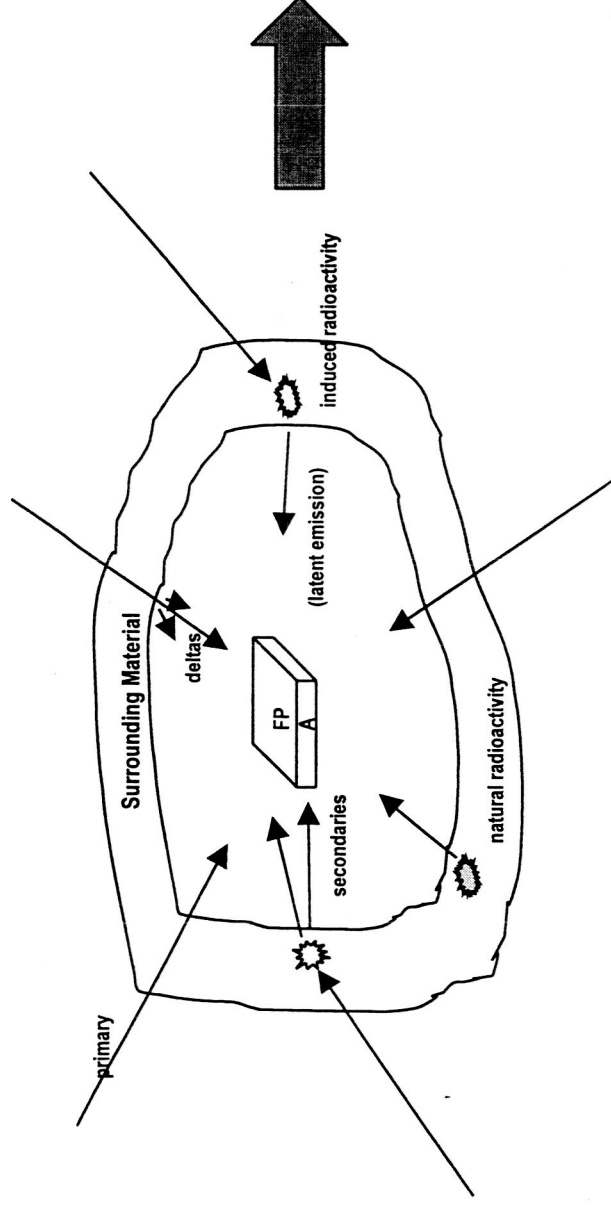
- Initial line source of minority carrier distribution based on particle LET and trajectory
- Drift and diffusion models applied collection models applied depending on particle location
- Charge carrier history ends when either collected or recombined
- Charge distributed to pixels across array in accordance with drift and diffusion
- Output is pulse height distributions, crosstalk characterization, FITS files, etc.



# Future Direction for Modeling on On-Orbit Prompt Response

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- Predict the environment at the FPA using GEANT4, MCNPX, NOVICE, and EASY
  - Requires detailed information about the spacecraft structure around the FPA
- Determine the response of the FPA using REACT



# Roadmap

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- Collaborators:
  - NASA/GSFC
  - Vanderbilt University
- Also coordinating with ESA efforts
- Near Term Goals
  - Compare GEANT4 results to other models
    - Ion track structure in Silicon
    - Proton-reaction recoil nuclei distributions
  - Develop CR TIP techniques to be capable of predicting heavy ion and proton SEE rates using existing models
  - Convert NASA's drift and diffusion modeling routines (called REACT) to be compatible with OOP
  - Proof of concept for establishing a parallel processing in Geant4
    - Vanderbilt has access to >120 node Cluster of >2GHz machines
  - Develop collaboration with Geant4 development team